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USING BOX-JENKINS MODEL TO FORECAST FISHERY DYNAMICS I:

IDENTIFICATION, ESTIMATION, AND CHECKING

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In this two part paper, the use of Box-Jenkins models for modeling and forecasting fisheries is explored. Part I explores in some detail the process of identifying and estimating a Box-Jenkins model, and how forecasts are made and updated. A model developed to forecast skipjack tuna, Katsuwonus pelamis, catches in Hawaii is used to illustrate the methodology. In part II, the strengths and weaknesses of models developed to forecast yellowfin tuna, Thunnus albacares, catches in the eastern Pacific and salmon runs in the Skeena River are discussed.

Forecasting techniques have improved greatly in the last few years, and research in fisheries management generally has not kept up with these advances. There are good reasons for considering forecasting models. Firstly, the needs of good forecasts are different from those of the usual stock assessment techniques. These latter techniques primarily are aimed at determining the (equilibrium) status or health of the stock. While the fit to the observed data used to estimate the stock assessment models vary from case to case, these models on the whole do not successfully predict the actual history of the stock for the next few time periods of interest.

A second reason for considering forecasting models is the weak statistical basis underlying both the general production model (Fox 1970, 1971, 1975) and such models as the Ricker spawner-recruit curve (Ricker 1954). Each of these techniques scales the dependent variable (catch or recruits) by the independent variable (effort or spawners), and then performs a least squares fit against a function of the independent variable. Several authors (Chayes 1949; Eberhardt 1970;

Atchley et al. 1976) have demonstrated that this procedure can introduce severe bias into the estimation procedure, so that even two uncorrelated random variables would appear to have a significant relationship. The general production model often uses a function not of effort, but of a weighted sum of the effort over the past several years. After scaling, effort is then estimated as a lagged variable of itself. Johnston (1972) shows that using ordinary least squares procedures in this instance again biases the estimated "goodness of fit."

Most importantly, however, is the fact that most fishery data are highly autocorrelated through time: An examination of the residuals in Fox (1971, Fig. 3B) clearly exhibit autoregressive behavior. The same can be said for most residuals from spawner-recruit curves. Granger and Newbold (1977) and Newbold and Davies (1978) have termed using ordinary least squares in these instances "spurious regression" and demonstrate how the estimated fit of the model is biased upward when the errors are misspecified.

Box-Jenkins models and other forecasting techniques are usually specifically designed to estimate parameters when the data are autocorrelated, including seasonal data. Moreover, the models are stochastic, rather than deterministic, reflecting the variability observed in most fisheries. Our preference for Box-Jenkins models over other forecasting techniques is more practical than anything else. Box-Jenkins models are well documented (see for example Anderson 1975; Box and Jenkins 1976; Granger and Newbold 1977), they are empirically constructed from the data rather than force fitted, and there are several packages available to perform the necessary computations. The results presented here were calculated

using a package originally developed by David Pack at Ohio State University; and now available through Automated Forecasting Systems.

II. THE DATA AND THE UNDERLYING MODEL

The data to be analyzed are landings of skipjack tuna by approximately 12 boats on Oahu 1964 through 1978. Each boat rarely stays out more than a day or two, and the raw data consist of the daily landings, broken down by boat, and for four size classes, large, medium, small, and extra small. For purposes of analysis, the data have been aggregated into monthly totals, with the total number of fishing trips used as the measure of fishing effort. The monthly catch and effort for the period 1964-78 are plotted in Figures 1 and 2.

There are several causes for the observed seasonal variability. Firstly, the tuna are only available seasonally in large numbers. Secondly, price considerations, particularly around Christmas and New Years when there is large demand, tend to spur fishing even when availability is low. Thirdly, with only 12 boats fishing, if 1 or 2 boats are not able to fish for a few weeks, the catch will drop sharply. Finally, environmental factors, particularly weather (such as bad seas) will affect the landings since the boats are unable to fish.

Folklore in Hawaii has it that the catch remains pretty much the same each year, no matter how many boats fish. Comitini (1977) examined the fishery using dummy variables and ordinary least squares to estimate a Cobbs-Douglas production function. He concludes among other things that natural fluctuations in resource availability are significant, but

does not include them in his analysis, nor does he provide a means for forecasting future catch. The National Marine Fisheries Service, using a regression model based on the previous year's catch, water temperature, and salinity at the start of the year make yearly predictions that have been mixed in accuracy. Monthly forecasts have been thought to be impracticable or impossible due to the variability in the data.

A feature of the data not examined in this paper is that prior to 1973, the catch of the large tuna and the total catch "track" together closely. After 1973 this is not so. There are several possible explanations for this, including the mercury scare in the early 1970's for large tuna, increased foreign fishing around Hawaii, and increased catches elsewhere in the Pacific. While this change in size composition does not affect our modeling of the total catch (as will be seen), it is certainly a trend worth analyzing in greater detail if more accurate forecasts are to be obtained.

Box-Jenkins models are based on autoregressive-integrated-moving-average models, or ARIMA models. These are linear, stochastic models that can describe fairly complex behavior. Unlike Parrish and MacCall (1978) say, who have gone to more highly nonlinear equations to model the fluctuations in fishery data, the approach here is to use less complex, linear models.

The modeling is based on the properties of stationary time series. A time series x_t is stationary if it has mean zero, and if the covariance between events x_t , x_{t-s} depends only on s and not on t . Many series are stationary after removing the estimated (observed) mean. Others have to be differenced in order to achieve stationary. It is convenient to



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use the backshift operator $B^j x_t = x_{t-j}$ when describing lags or differencing. The initial step then is to transform and difference the data as necessary to achieve stationarity. Given the new series $z_t = (1 - B^d)x_t$, a mixture of autoregressive and moving average models are sought. Autoregressive models are lags on the past history of the time series:

$$z_t = \phi_1 z_{t-1} + \phi_2 z_{t-2} + \dots + \phi_p z_{t-p} + a_t$$

or equivalently:

$$(1 - \phi_1 B - \phi_2 B^2 - \dots - \phi_p B^p) z_t = a_t$$

and moving average models are lags on the past noise or error a_t :

$$z_t = a_t - \theta_1 a_{t-1} - \theta_2 a_{t-2} - \dots - \theta_q a_{t-q}$$

or:

$$z_t = (1 - \theta_1 B - \theta_2 B^2 - \dots - \theta_q B^q) a_t$$

A model that has both moving average and autoregressive parameters is a mixed autoregressive moving average model. The general representation is:

$$(1 - \phi_1 B - \phi_2 B^2 - \dots - \phi_p B^p) (1 - B^d) x_t = (1 - \theta_1 B - \theta_2 B^2 - \dots - \theta_q B^q) a_t.$$

III. MODEL IDENTIFICATION

The first step in the modeling process is to use properties of the data to tentatively identify a model. In Box-Jenkins techniques, even if a multivariate model (i.e., a model based on catch and effort) is the ultimate goal, univariate models of each series are first constructed. Often the univariate model produces forecasts that are almost as accurate as the multivariate model forecast.

Our procedure was to fit initially a model from the data for January 1964 through July 1977, and then forecast to December 1978. If the forecasts seemed reasonable, the parameters would be reestimated using the data for January 1964 through December 1978, and then monthly forecasts for 1979 would be made. (To make clear the feedback nature of identification, estimation, and checking in Box-Jenkins models, results from models fixed to 163 mo and 180 mo of data are intermingled, but clearly labeled.) In both cases, the forecasts are of data points not used in identifying the model or estimating the parameters.

A tentative model can be identified by estimating the regular and partial autocorrelation functions for each series. These are shown in Figures 3-4. Significant is the undamped sinusoidal behavior of each, with a period of 12 mo. Failure of both the regular and partial autocorrelation functions to go to zero is a sign of a nonstationary series, and the need for differencing. In this instance, a seasonal model is suggested, so that twelfth differences were taken, that is

$$z_t = (1 - B^{12})x_t.$$

The estimated regular and partial autocorrelation functions for the differenced catch and effort series are given in Tables 1 and 2.

There are several ways to proceed from here, but suspecting a multiplicative and seasonal model, appendix 9.1 in Box/Jenkins (1976) was consulted. This lists special characteristics of the autocovariances of the multiplicative seasonal models most often encountered. In particular, a seasonal model with period s of the form:

$$z_t = (1 - \theta_1 B - \theta_2 B^2) (1 - \theta_1 B^s - \theta_2 B^{2s}) a_t \quad (3.1)$$

has the special characteristics:

$$p_{s-2} = p_{s+2}$$

$$p_{s-1} = p_{s+1}$$

$$p_{2s-2} = p_{2s+2}$$

$$p_{2s-1} = p_{2s+1}$$

and should have a significant autocorrelation at lag s . For $s = 12$,

Tables 1,2 Tables 1 and 2 both show a highly significant autocorrelation at lag 12.

Moreover, the implied equalities for effort are: $-0.08 = -0.08$;

$-0.20 = -0.18$; $0.05 = -0.07$; $0.04 = 0.00$. The implied equalities for

catch are: $-0.12 = -0.15$; $-0.21 = -0.21$; $-0.08 = -0.06$; $-0.08 = -0.06$.

As these estimated values come close to the theoretical properties of model (3.1), this was accepted as a tentative model for the two time-series.

IV. ESTIMATION AND CHECKING

There are two methods generally used to estimate parameters for Box-Jenkins parameters. The first involves maximizing the conditional likelihood, the second the unconditional. In some packages, the program will request if it is desired to suppress backforecasting. Backforecasting is used in the unconditional estimation. When backforecasting is used, the algorithm is more sensitive to starting values and takes longer to execute. The estimates, however, usually have a smaller residual sum of squares than when backforecasting is suppressed. A procedure often used is to first estimate the parameters suppressing backforecasting, and then use these estimates as starting values for the unconditional estimation.

The estimate for both catch and effort for model (3.1) are given in Tables 3,4 Tables 3 and 4. There are two major techniques for checking for model inadequacy. The first is to calculate the estimated regular and partial autocorrelations of the model residuals, and the second is to overfit the model. The estimated regular and partial autocorrelations for the residuals from each series when backforecasting is used are given in Tables 5,6 Tables 5 and 6. For the effort series, there is no sign of lack of fit. For the catch series, however, additional terms of lag for three and four are suggested. An overspecified model:

$$z_t = (1 - \theta_1 B - \theta_2 B^2 - \theta_3 B^3 - \theta_4 B^4) (1 - \theta_1 B^{12})$$

was fit to both time series. The results are summarized in Tables 7,8 Tables 7 and 8. The regular and partial autocorrelation functions (not shown) show no sign of additional lags or trend. Box and Jenkins (1976, p. 291) give a

portmanteau chi square statistic to test whether the residual series can adequately be described as white noise. The test statistic, given in Tables 7 and 8, suggest no reason to question the models' adequacy.

V. TRANSFER FUNCTION MODELS

If both the catch time series, say y_t , and the effort time series, say x_t , have been suitably transformed so that the resulting series are stationary, a transfer function can be estimated of the form:

$$(1 - \delta_1 B - \delta_2 B^2 - \dots - \delta_r B^r) x_t = (\omega_0 - \omega_1 B - \omega_2 B^2 - \dots - \omega_s B^s) y_{t-b} + \eta_t$$

where η_t is not assumed to be white noise, but itself can be modeled as an autoregressive-moving average process of a_t .

The procedure for identifying and estimating a transfer function model are similar to those for the univariate model, except that attention is focused on the estimated cross-correlation function between the "prewhitened" catch and effort series. Series are prewhitened if they are reduced to the residuals left from a given model. In this instance, both series are prewhitened by the univariate model for effort estimated in section IV. The estimated correlation function, impulse response function, and residual noise autocorrelation function are given in Table 9. The estimated autocorrelation function for the noise is similar to the original univariate autocorrelations, suggesting a noise model of the form:

$$\eta_t = (1 - \theta_1 B - \theta_2 B^2 - \theta_3 B^3 - \theta_4 B^4) (1 - \theta_1 B^{12}) a_t \quad (5.1)$$

Based on guidelines in Box and Jenkins (1977, p. 386-388) and knowledge of the fishery, two models were hypothesized:

$$(1 - B^{12})y_t = (\omega_0) (1 - B^{12})x_t + \eta_t \quad (5.2)$$

and:
$$(1 - \delta_1 B - \delta_2 B^2)(1 - B^{12})y_t = (\omega_0 - \omega_1 B - \omega_2 B^2)(1 - B^{12})x_t + \eta_t \quad (5.3)$$

ables 10,11

Tables 10 and 11 summarize the estimates when backforecasting is used in estimating the parameters for (5.2) and (5.3). The chi square statistics show no reason to suspect model inadequacy. The residuals show no significant cross-correlation with total catch, when $1/\sqrt{180}$ (180 observations in the series) is used as a rough standard error. The residual autocorrelation function shows spikes around lag 15 that are higher than would be desired, but overall the fit is reasonable, and the model residuals could reasonably be modeled as white noise.

VI. DISCUSSION AND FORECASTS

The three models that were fit to forecast the total monthly skipjack tuna catch can be better interpreted when written in difference equation form. The univariate model becomes:

$$\begin{aligned} y_t = & y_{t-12} + (a_t + 0.538 a_{t-1} + 0.438 a_{t-2} + 0.412 a_{t-3} + 0.309 a_{t-4}) \\ & - (0.996 a_{t-12} + 0.535 a_{t-13} + 0.436 a_{t-14} + 0.410 a_{t-15} + 0.308 a_{t-16}) \end{aligned} \quad (6.1)$$

That is, the catch this month is equal to the catch the same month last year, plus the difference between a weighted sum of this year's forecasting errors compared to last year's. The model checks to see how far off the mean trend this year has been compared to last year, and adjusts the predicted catch according. The model that has been derived is completely consistent with the local folklore, only it gives a method to adjust the forecast to include the year to year variability. The other expected result is that the residual mean square is large (115, 170), despite the fact that the residuals have been reduced to white noise. The model was constructed from the data, but is consistent with the experience and perceived knowledge of people familiar with the fishery.

This impression of a yearly cycle with variability is reinforced when examining the polynomial representation of the model (3.1). The value of Θ is nearly one. Thus, the term $(1 - B^{12})$ appears on both sides of the equation, and can be cancelled. Abraham and Box (1978) show that this is sufficient reason to suspect a deterministic cosine function trend.

This approach is not used since the deterministic trend would not self-correct to the past errors in the forecasts.

The two multivariate models are:

$$\begin{aligned}
 y_t = & 8.003 x_t + (y_{t-12} - 8.003 x_t) \\
 & + (a_t + 0.489 a_{t-1} + 0.326 a_{t-2} + 0.149 a_{t-3} + 0.175 a_{t-4}) \quad (6.2) \\
 & - (0.996 a_{t-12} + 0.487 a_{t-13} + 0.325 a_{t-14} + 0.148 a_{t-15} + 0.174 a_{t-16})
 \end{aligned}$$

and

$$\begin{aligned}
y_t = & 8.186 x_t + (0.866 y_{t-1} - 6.742 x_{t-1}) - (0.708 y_{t-2} - 7.313 x_{t-3}) \\
& + (y_{t-12} - 8.186 x_{t-12}) + (0.866 y_{t-13} - 6.752 x_{t-13}) - (0.708 y_{t-14} - 7.313 x_{t-14}) \\
& + (a_t + 0.470 a_{t-1} + 0.332 a_{t-2} + 0.172 a_{t-3} + 0.217 a_{t-4}) \quad (6.3) \\
& - (0.995 a_{t-12} + 0.468 a_{t-13} + 0.331 a_{t-14} + 0.171 a_{t-15} + 0.216 a_{t-16})
\end{aligned}$$

The model (6.12) predicts that catch this month is a function of the relative catch and effort in the same month last year, corrected by the relative forecasting errors the last 4 mo this year less the same errors the year before. The model (6.3) is similar, except that the catch and effort for the 4 mo previous, both this year and last, are used in the prediction.

Forecasts can be made using any of the three models by substituting expected values for unknown values. If T is the base period of the forecast, and the last observed period, then for $\ell > 0$, the expectation of $a_{t+\ell}$ is zero. The expected effort series can be generated by the univariate effort model, and for each period $T+\ell$, the predicted catch and effort are used in the forecast as the expected value.

Table 12

Monthly forecasts for 1979 are given in Table 12. It can be seen that the models perform adequately. January is the worst month, but January 1979 had unusually severe weather and relatively little fishing. The forecasts rise a little too quickly for April, but by May the forecasts are fairly accurate.

Table 13

More importantly, a desirable feature of any forecast is an ability to constant self-correct to the observed forecasting errors. Table 13 gives the same three forecasts after the January-April 1979 data has been included in the data set. The updated forecasts lower the May estimate, since January-February were bad months, but increase the predicted catch in late summer. Experience with each of the models is that while there may be considerable month to month error, the forecasts quickly self-correct. Over a 12-15 mo period, the forecasting errors can be expected to cancel each other out, providing a relatively accurate forecast for the year. The updated forecasts predict a yearly catch of about 3,300 metric tons (MT), with the three forecasts differing less than 100 MT. This is almost 1,000 MT better than 1978. The earlier catch record, plus observations from the fishermen, would seem to support this optimistic forecast.

Improved forecasts might be expected if effective trips per month is used as the input series instead of total trips per month. Also, breaking the catch into size classes may improve the forecast, since the dynamics of the size classes differ, and the total catch dynamics is a mixing of each of these series. These possibilities will be reported on in future papers.

VII. SUMMARY

Box-Jenkins models have been proposed as an alternate model for forecasting fishery data. ARIMA models provide maximum likelihood estimators that are not biased when the data is seasonal and autocorrelated, and when a variable is lagged on itself. Techniques are explored which allow the

model to be constructed from the data up, rather than from questionable theoretical models. The procedure is illustrated on skipjack tuna catches in Hawaii, which traditionally has been considered too variable to forecast on a monthly basis in a reasonable manner.

Part II of this paper will examine models of the yellowfin tuna catch in the Pacific and salmon runs on the Skeena River. In part II, less emphasis will be given to how to identify the model, and more emphasis will be given to the problems of forecasting complex systems with relatively short time series. This leads to large estimated standard errors for parameters with values much different from zero. Alternate methods of estimating the transfer function between catch and effort will also be examined.

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Table 1.--Autocorrelation functions for 12th differenced effort series.

Lag	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Regular auto.	0.39	0.17	0.20	0.16	0.10	0.04	0.03	0.07	-0.02	-0.08	-0.20	-0.45	-0.18	-0.08
S.E.	0.08	0.09	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.12	0.12
- - - - -	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Partial auto.	0.39	0.03	0.15	0.03	0.01	-0.04	0.00	0.00	-0.08	-0.07	-0.19	-0.39	0.15	0.04

Lag	15	16	17	18	19	20	21	22	23	24	25	26	27
Regular auto.	-0.18	-0.13	-0.12	-0.17	-0.15	-0.17	-0.12	0.05	0.04	0.02	0.00	-0.07	0.03
S.E.	0.12	0.12	0.12	0.12	0.12	0.12	0.13	0.13	0.13	0.13	0.13	0.13	0.13
- - - - -	-	-	-	-	-	-	-	-	-	-	-	-	-
Partial auto.	-0.03	0.02	-0.07	-0.14	-0.01	-0.02	-0.05	0.16	-0.08	-0.19	0.05	-0.12	0.03

Table 2.--Autocorrelation functions for 12th differenced catch.

Lag	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Regular auto.	0.58	0.40	0.33	0.20	0.11	0.05	0.01	0.02	-0.06	-0.12	-0.21	-0.38	-0.21	-0.15
S.E.	0.08	0.11	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.13	0.13	0.14	0.14
- - - - -	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Partial auto.	0.58	0.09	0.10	-0.07	-0.03	-0.04	-0.00	0.04	-0.11	-0.07	-0.17	-0.29	0.28	0.03

Lag	15	16	17	18	19	20	21	22	23	24	25	26	27
Regular auto.	-0.16	-0.12	-0.08	-0.09	-0.08	-0.12	-0.10	-0.08	-0.08	-0.09	-0.06	-0.06	-0.05
S.E.	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14
- - - - -	-	-	-	-	-	-	-	-	-	-	-	-	-
Partial auto.	-0.01	-0.06	-0.02	-0.07	0.02	-0.05	-0.04	-0.04	-0.11	-0.17	-0.19	-0.01	-0.02

Table 3.--Parameter estimates for effort model

$$z_t = (1 - \theta_1 B - \theta_2 B^2) (1 - \theta_1 B^{12} - \theta_2 B^{24}) a_t .$$

Parameter	Estimate suppressing backforecasting	Standard error	Estimate using backforecasting	Standard error
θ_1	-0.38349	0.07942	-0.44756	0.07886
θ_2	-0.11326	0.07996	-0.12795	0.07911
Θ_1	0.5894	0.08122	0.99493	0.00650
Θ_2	0.00069	0.08609	--	--
χ^2 statistic on residuals	26.894 with 44 d.f.		37.319 with 45 d.f.	
Residual mean square	1,018.60		755.270	
Residual standard error	31.915		27.482	
Residual mean	1.629		0.5338	

Based on 180 observations.

Table 4.--Parameter estimates for catch model

$$z_t = (1 - \theta_1 B - \theta_2 B^2) (1 - \theta_1 B^{12} - \theta_2 B^{24}) a_t.$$

Parameter	Estimate suppressing backforecasting	Standard error
θ_1	-0. 54100	0.08190
θ_2	-0.22745	0.08235
θ_1	0.75314	0.08718
θ_2	0.05184	0.09256
χ^2 statistic on residuals	27.470 with 43 d.f.	
Residual mean square	165410	
Residual standard error	406.71	
Residual mean	17.506	

Based on 163 observations.

Table 7.--Parameter estimates for effort model

$$(1 - B^{12}) x_t = (1 - \theta_1 B - \theta_2 B^2 - \theta_3 B^3 - \theta_4 B^4 - \theta_5 B^5) (1 - \theta_1 B^{12}) a_t .$$

Parameter	Estimate suppressing backforecasting	Standard error	Estimate using backforecasting	Standard error
θ_1	-0.36746	0.08004	-0.43862	0.07930
θ_2	-0.14976	0.08412	-0.18144	0.08590
θ_3	-0.16111	0.08458	-0.15377	0.08617
θ_4	-0.17096	0.08454	-0.16298	0.08593
θ_5	-0.11547	0.08089	-0.17291	0.07998
θ_{12}	0.59065	0.06431	0.99483	0.00033
χ^2 statistic on residuals	20.696 with 42 d.f.		27.494 with 42 d.f.	
Residual mean square	1,000.40		752.67	
Residual standard error	31.629		27.435	
Residual mean	0.82151		0.35175	

Based on 180 observations.

Table 8.--Parameter estimates for the catch model

$$(1 - B^{12}) x_t = (1 - \theta_1 B - \theta_2 B^2 - \theta_3 B^3 - \theta_4 B^4 - \theta_5 B^5) (1 - \theta_1 B^{12}) a_t .$$

Parameter	Estimate suppressing backforecasting	Standard error	Estimate using backforecasting	Standard error
θ_1	-0.55368	0.07972	-0.53771	0.07462
θ_2	-0.35882	0.08989	-0.43825	0.07543
θ_3	-0.33817	0.09056	-0.41197	0.01144
θ_4	-0.24282	0.09012	-0.30909	0.07479
θ_5	-0.12294	0.07994	-0.14974	0.07440
θ_1	0.76951	0.05062	0.99585	0.00825
χ^2 statistic on residuals	15.092 with 42 d.f.		20.384 with 42 d.f.	
Residual mean square	143240		115170	
Residual standard error	378.47		339.37	
Residual mean	2.1150		3.3299	

Based on 180 observations.

Table 9.--Estimated cross-correlation function, impulse response function,
and noise autocovariance function for a catch-effort transfer model.

Lag	0	1	2	3	4	5	6	7	8	9	10	11	12	13
Est. cross- corr.	0.651	0.080	0.070	0.086	-0.033	0.044	-0.098	0.099	0.103	-0.017	0.043	-0.040	-0.20	0.026
Est. noise auto.	--	0.49	0.21	0.16	0.16	0.10	0.07	0.03	0.13	0.14	-0.05	-0.14	-0.26	-0.05
S.E.		0.10	0.12	0.12	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.14
Est. impulse response wts.	8.409	1.035	0.903	1.111	-0.431	0.566	-1.269	1.276	1.334	-0.215	0.556	-0.517	-1.555	0.338
Lag	14	15	16	17	18	19	20	21	22	23	24	25	26	
Est. cross- corr.	-0.109	0.003	-0.098	0.014	-0.110	-0.037	0.006	-0.006	-0.108	0.012	-0.108	-0.001	-0.108	
Est. noise auto.	0.05	-0.12	-0.16	-0.01	-0.05	-0.12	-0.12	-0.16	-0.11	-0.18	-0.21	-0.09	-0.08	
S.E.	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.15	0.15	0.15	0.15	
Est. impulse response wts.	-1.404	-0.038	-0.415	0.043	-1.271	0.185	-1.422	-0.475	0.080	-0.075	-1.393	0.181	-1.390	

Table 10.--Parameter estimates for transfer model

$$(1 - B^{12})y_t = \omega_0(1 - B^{12})x_t + (1 - \theta_1 B - \theta_2 B^2 - \theta_3 B^3 - \theta_4 B^4) (1 - \theta_1 B^{12}) a_t .$$

Parameter	Estimate suppressing backforecasting	Standard error	Estimate using backforecasting	Standard error
ω_0	7.5989	0.69403	8.0003	0.83561
θ_1	-0.47621	0.07993	-0.48894	0.07851
θ_2	-0.32874	0.08734	-0.32633	0.08541
θ_3	-0.17034	0.08803	-0.14853	0.08666
θ_4	-0.20033	0.07905	-0.17506	0.07822
θ_1	0.83384	0.05271	0.99587	0.00707
χ^2 statistic on residuals	34.953 with 43 d.f.		32.018 on 43 d.f.	
Residual mean square	83,323		71,300	
Residual standard error	288.66		267.02	
Residual mean	-15.152		0.18650	

Based on 180 observations

Table 11.--Parameter estimates for transfer model

$$(1 - \delta_1 B - \delta_2 B^2) (1 - B^{12}) x_t = (\omega_0 - \omega_1 B - \omega_2 B^2) (1 - B^{12}) x_t \\ + (1 - \theta_1 B - \theta_2 B^2 - \theta_3 B^3 - \theta_4 B^4) (1 - \theta_1 B^{12}) a_t.$$

Parameter	Estimate suppressing backforecasting	Standard error	Estimate using backforecasting	Standard error
δ_1	0.01286	0.30389	0.86672	0.22308
δ_2	0.88121	0.28641	-0.70763	0.21659
ω_0	7.3488	0.73352	8.1855	0.82832
ω_1	-1.3011	2.16847	6.7421	1.71214
ω_2	6.8509	2.34577	-7.3133	1.58459
θ_1	-0.49924	0.08302	-0.46980	0.08013
θ_2	-0.29495	0.09102	-0.33234	0.08870
θ_3	-0.16384	0.09191	-0.17199	0.09012
θ_4	-0.13639	0.08352	-0.21746	0.08098
θ_1	0.83311	0.05511	0.99543	0.00623
χ^2 statistic on residual	33.067 with 43 d.f.		38.906 with 43 d.f.	
Residual mean square	85,673		69,066	
Residual standard error	292.70		262.80	
Residual mean	-1.9979		-2.4666	

Based on 180 observations

Table 12.--Catch forecasts for 1979 from the three models (MT).

Month	Model				Univariate	Observed
	$(1 - B^{12})y_t = \omega_0(1 - B^{12})x_t + \eta_t$	$(1 - \delta_1 B - \delta_2 B^2)(1 - B^{12})y_t$	$(\omega_0 - \omega_1 B - \omega_2 B^2)(1 - B^{12})x_t + \eta_t$			
Jan.	102.24	157.48		159.97	52.6488	
Feb.	78.91	123.32		117.81	74.1184	
Mar.	121.86	118.83		108.40	102.4088	
Apr.	202.05	169.75		175.82	131.0658	
May	423.40	406.87		423.95	470.5450	
June	595.39	605.68		598.17		
July	666.16	684.99		607.07		
Aug.	528.09	535.73		523.14		
Sept.	297.96	294.92		291.97		
Oct.	224.28	216.64		222.96		
Nov.	173.99	168.83		172.94		
Dec.	133.22	131.61		132.58		
Total	3,544.55	3,614.65		3,594.78		

Table 13.--Updated forecasts of total catch (MT).

Month	Model			Univariate	Observed
	$(1 - B^{12})y_t = \omega_0(1 - B^{12})x_t + \eta_t$	$(1 - \delta_1 B - \delta_2 B^2)(1 - B^{12})y_t$	$= (\omega_0 - \omega_1 B - \omega_2 B^2)(1 - B^{12})x_t + \eta_t$		
May	393.214	382.430		401.874	470.545
June	547.014	586.400		589.524	
July	644.638	705.137		668.895	
Aug.	500.151	527.945		521.456	
Sept.	293.130	283.067		289.516	
Oct.	220.557	197.953		222.806	
Nov.	174.567	164.720		173.594	
Dec.	130.947	136.831		133.148	
Total	2,904.218	2,983.983		3,000.813	

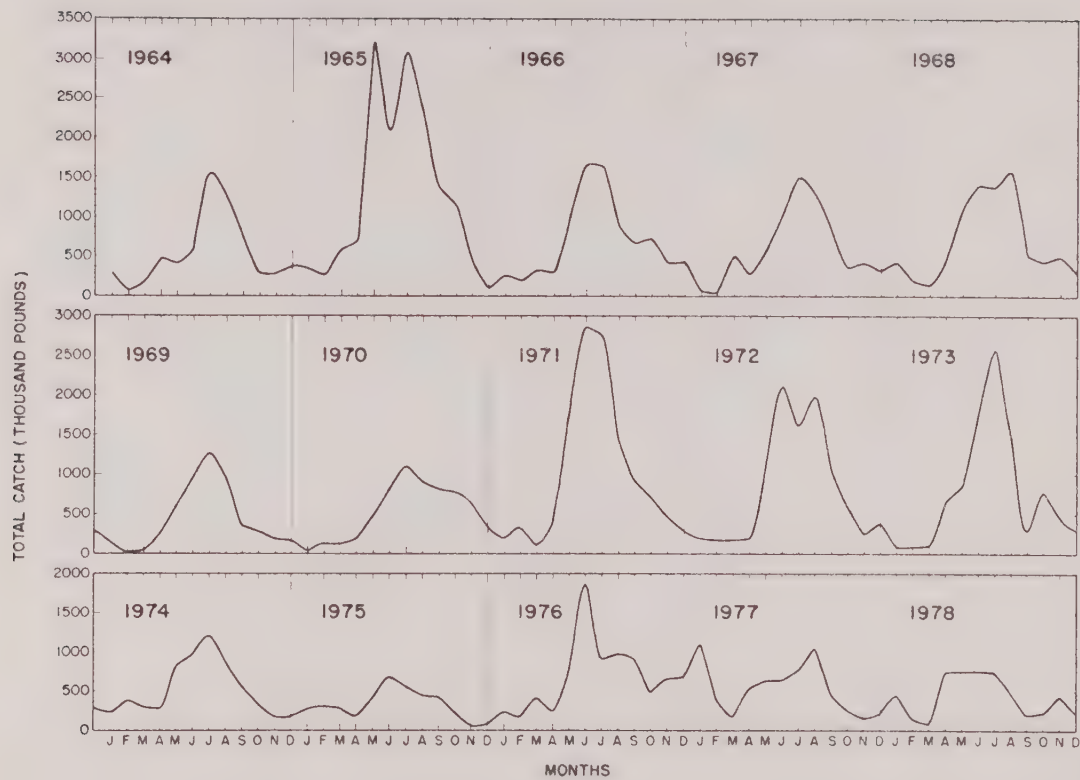


Figure 1.--Level of skipjack tuna catch by month, 1964-78.

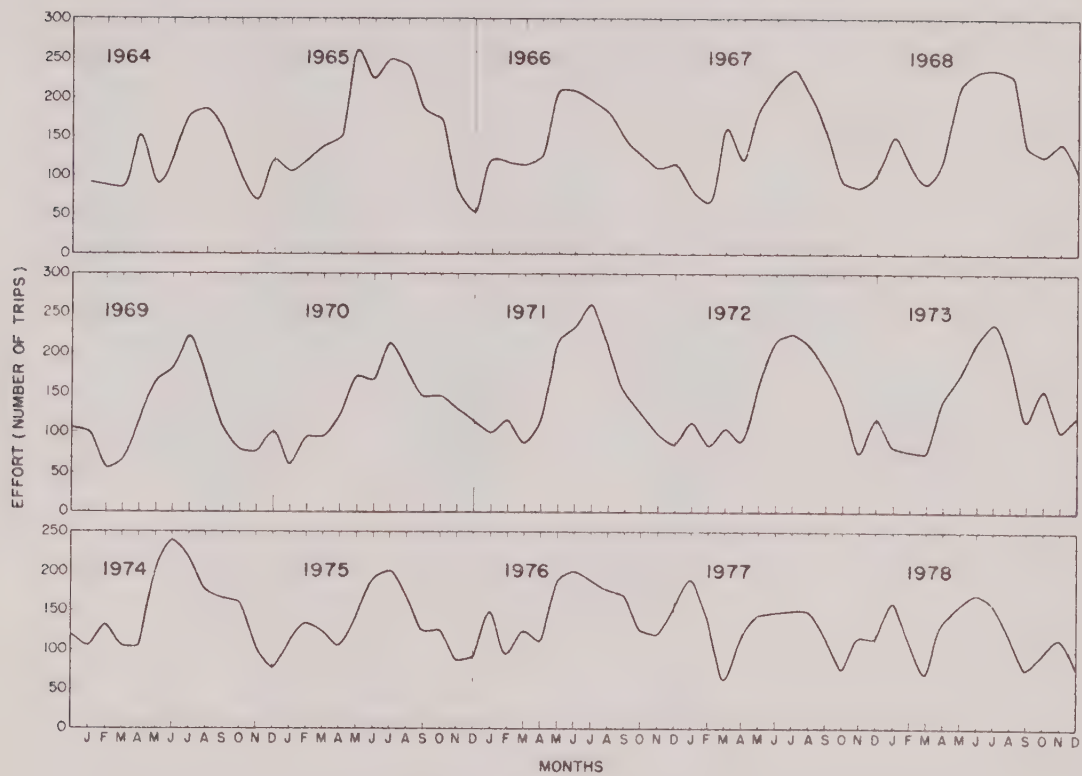


Figure 2.--Number of fishing trips per month, 1964-78.

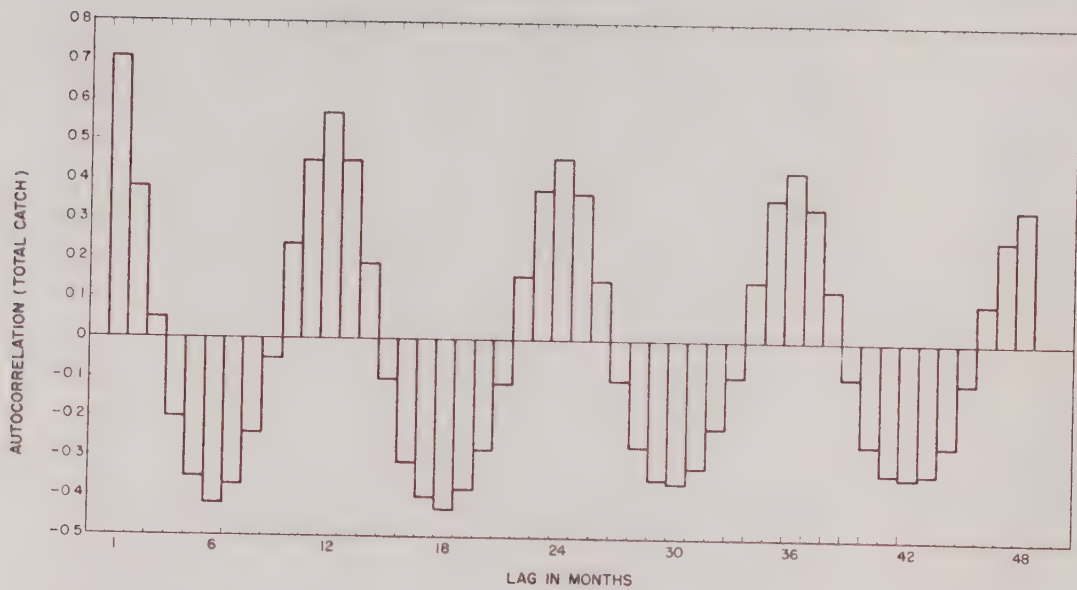


Figure 3.--Estimated total catch autocorrelation function.

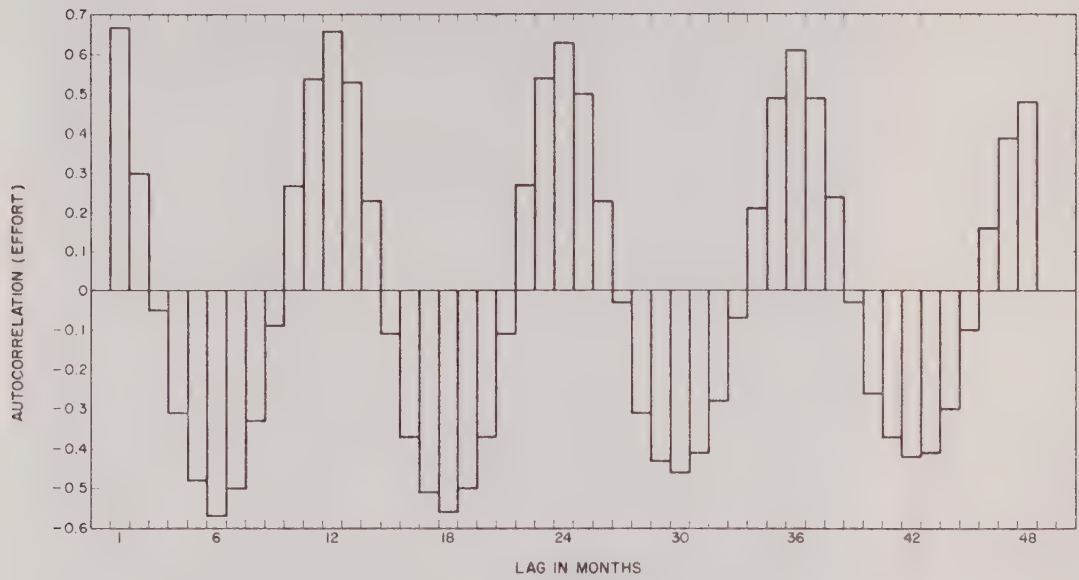


Figure 4.--Estimated effort autocorrelation function.

U.S. DEPARTMENT OF COMMERCE
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
NATIONAL MARINE FISHERIES SERVICE
SOUTHWEST FISHERIES CENTER
HONOLULU LABORATORY

KEWALO RESEARCH FACILITY



AUGUST 1979

This brochure does not constitute a publication and is for information only. All data herein are to be considered provisional.

ADMINISTRATIVE REPORT H-79-11

FORWARD

In the important commercial tuna fisheries of the world a major biological problem is the prediction of the distribution and abundance of the various species of tunas comprising the resource. Analyses of environmental data in the Pacific over the years have provided correlations between skipjack tuna distribution and various oceanographic and meteorological variables but the mechanisms determining the distribution, availability, and migration of tunas are not completely known. Temperature, oxygen, salinity, and food availability all influence tuna movements and limit their vertical and horizontal distribution. The Kewalo Research Facility of the Honolulu Laboratory is in the midst of an ongoing program to examine the effects of the most important environmental parameters on the behavior and physiology of tunas, and thus ultimately, their effects on the distribution, availability, and movements of tunas. This knowledge will be a major contribution to the science of fishery prediction.

The Honolulu Laboratory foresees the future role of the Kewalo Research Facility as an international gathering place for scientists of varied backgrounds and disciplines. The past two decades of quality research and the uniqueness of its facility have engendered an enviable reputation for the Kewalo Research Facility throughout the world. During this period many respected scientists from around the world have taken the opportunity to work with tunas under laboratory conditions at our facility.

To continue the high quality work and to press forward in more innovative research will require researchers possessing a high degree of specialization in various disciplines including physiology, biochemistry, hydromechanics, and electronics. Without doubt the many attributes of the Kewalo Research Facility will continue to attract well qualified scientists to its doors in the future.

THE KEWALO RESEARCH FACILITY

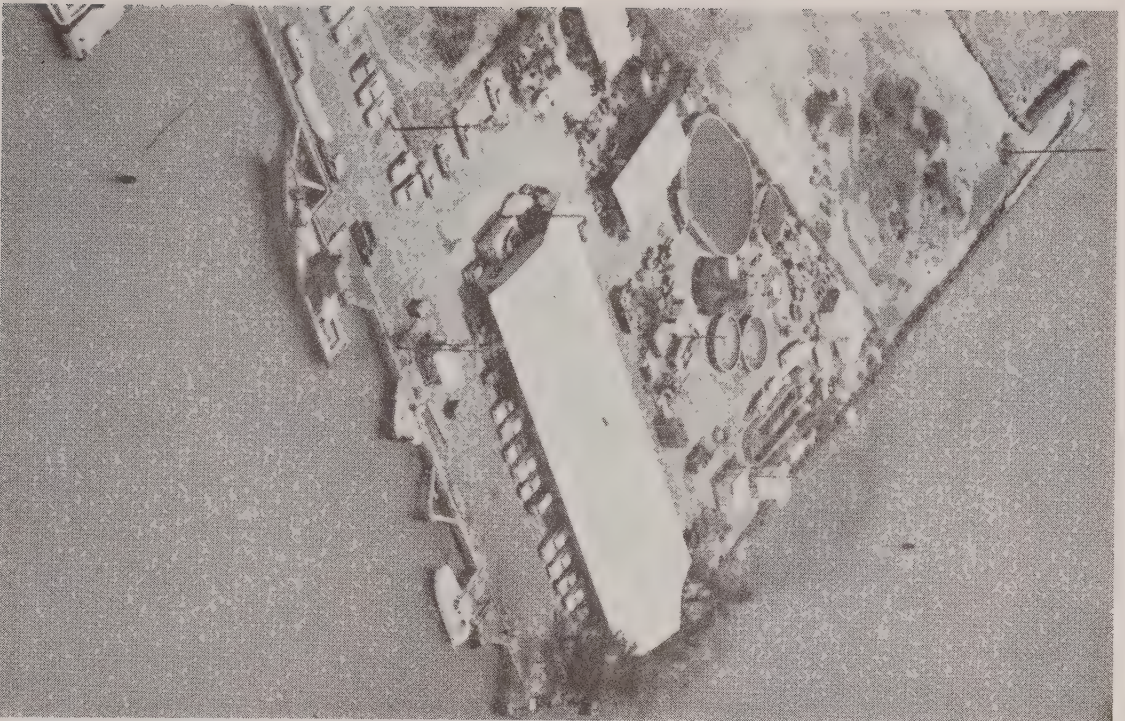
Kewalo--literally, the word can be defined as "the calling" (as an echo). Kewalo has also been translated as "the place of wailing." Historical descriptions of the area on the island of Oahu called Kewalo give meaning to the translation, "the place of wailing." In ancient times the section of land called Kewalo contained a spring, which before the conversion to Christianity, was used as the place where human sacrifices such as kauwa (outcasts) were first drowned before being taken to the Heiau of Kanelaanu on the slopes of Punchbowl for burning in the imu ahi (fire oven).

Kewalo, as part of the modern city of Honolulu, of course, is no longer used for such esoteric purposes as a place for drowning people. Kewalo (and Kewalo Basin) today is an area supporting many commercial and business activities. Kewalo Basin is the home of many commercial and recreational fishing boats, a seafood cannery, a fresh fish auction house, and other marine related enterprises. Kewalo Basin is also the site of the Honolulu Laboratory's Kewalo Research Facility.

BACKGROUND

The site occupied by the Kewalo Research Facility was once a shallow, submerged coral reef. In 1945 the U.S. Navy dredged a small harbor in the coral reef to create Kewalo Basin, which was later turned over to the Territory of Hawaii. Subsequently, the harbor was enlarged and artificial and sanitary fill was used to create protecting land areas on the south and east sides of the harbor basin.

In July 1958, the Honolulu Laboratory, National Marine Fisheries Service, National Oceanic and Atmospheric Administration (NOAA), U.S. Department of Commerce, which was then a part





Specially designed fiberglass transport tanks are used at sea in collecting tunas for use in experimental behavioral and physiological studies in shoreside tanks. The transport tanks are designed so that tunas caught on pole and lines using barbless hooks can easily be dropped in them without being handled. When the vessel returns to Kewalo Basin with a load of live tunas, a mobile crane lifts the 1,893-liter (500-gal) tank and delivers it over the short distance to the holding tanks. There the special design of the transport tanks allows the fish to swim out freely into the shoreside holding tanks. This handling technique which has evolved over the years minimizes shock to the fish, thus assuring a higher survival rate.

Live tunas are also collected by cooperating commercial pole-and-line fishermen. Using similar capturing and handling techniques, the commercial fishermen bring back live tuna in their vessel's bait holding tanks. At dockside the fish are dipped with plastic lined dip nets from the baitwells to the transport tanks and then transported to the holding tanks.

of the Fish and Wildlife Service, U.S. Department of the Interior, negotiated a lease to the grounds and building on the spit of artificially created land at the southeast entrance of Kewalo Basin to establish the Kewalo Research Facility. The facility has a low profile and goes unnoticed by the many surfers and fishermen that frequent the area. But within the 0.4 hectare (0.98 acre) area is a truly remarkable research facility. The main building has over 1,003.4 m² (10,800 sq ft) of space and houses offices and laboratories tailored for various research activities, a machine shop, and storage areas. On the adjoining grounds has been dug a saltwater well that has the capacity to produce over 3,785 liters (1,000 gal) per minute of high quality coral filtered seawater. The filtered seawater is pumped to an aerator to be oxygenated and then distributed to various tanks including a series of five 75,706-liter (20,000-gal) circular pools that can be observed from a tower, a 757,060-liter (200,000-gal) oceanarium, and specially designed experimental tanks of various sizes.

The Kewalo Research Facility still remains today as it did soon after it was first established as the only research center in the world that is able to collect and maintain live tunas throughout the year for use in behavioral and physiological research. Indeed, this international reputation has attracted and still attracts established scientists of diverse backgrounds and expertise to this facility where experiments requiring live tunas as laboratory animals can be conducted.

RESEARCH ACTIVITIES

Early Work

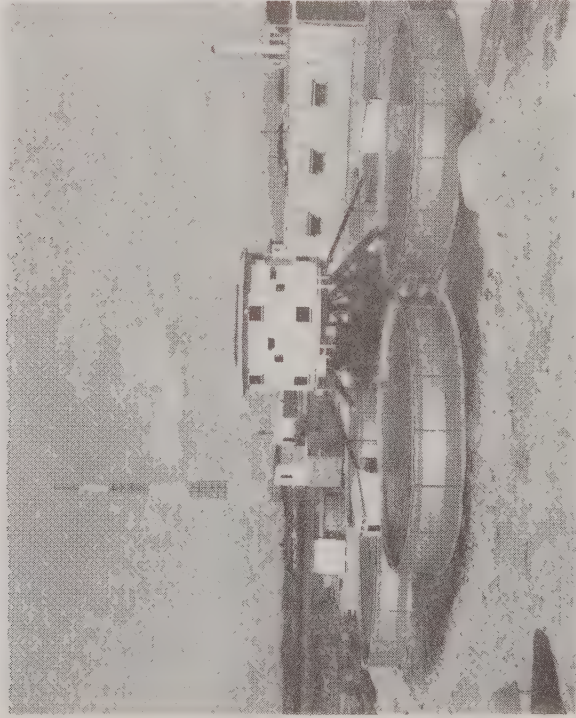
Tunas are widely distributed in the world oceans and are the bases of many important commercial fisheries. Despite their wide distribution and economic value very little research had been done with live specimens, probably in part because of

the difficulty in keeping them alive in captivity. Because of the limited knowledge available on live tunas as experimental animals, the early research was aimed at collecting data that would serve as the foundation for future investigations. This early work produced interesting facts about tunas.

- Tunas are heavier than water and must continuously swim to (1) keep afloat and (2) breathe by passing oxygen rich water over their gills. Tunas would sink and suffocate if they stopped swimming.
- The basal swimming speed of tunas is dependent upon the lifting area of fins and the density of the fish, and is not a function of respiration or a search for food.
- All tunas have made the following adaptations for continuous basal swimming: (1) a high hemoglobin level in their blood to carry more oxygen and nutrients to maintain continuous muscle activity; (2) compared to other fishes, possess a larger proportion of dark muscle that is specialized, like muscles of the heart, for continuous contractions; (3) possess a streamlined body shape to reduce drag.

- In larger species of tunas, two morphological features evolved to reduce energy required to keep afloat. First, pectoral fins got larger to produce more lift; second, when the pectorals were insufficient, gas bladders developed to decrease density. Although gas bladders are very effective in reducing density of fish, they limit the streamlined tuna to the deeper layers of the ocean. A fast vertical ascent to the surface would cause large changes in volume and in the extreme, burst the gas bladder.

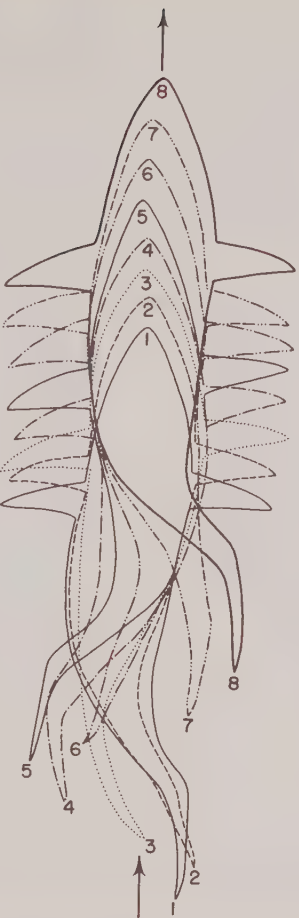
Other early experiments with tunas were designed to determine their sensory abilities--how well they can smell, taste, hear, and see. The rationale for these studies was that a



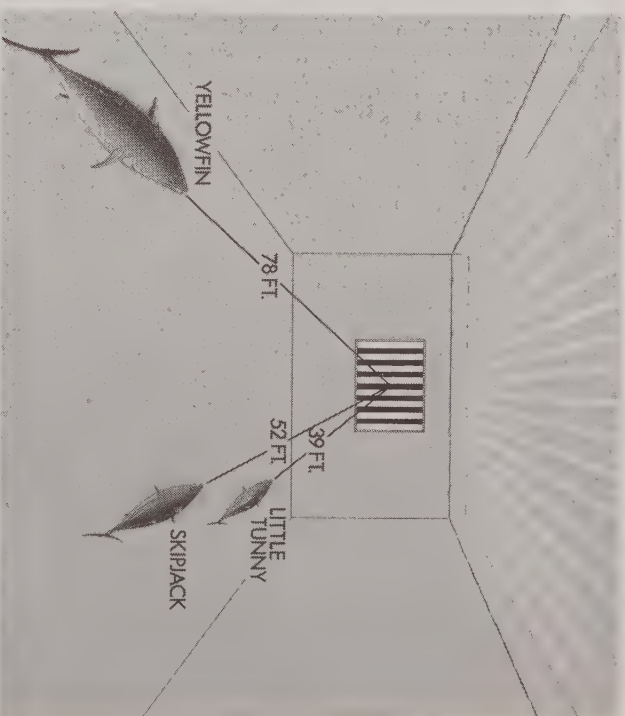
Much of the early tuna behavioral experiments were conducted in the tank-observational tower complex. The observation tower houses equipment to record behavior, water temperature, and light. It also has two windows facing each tank. Food to reinforce desired behavioral responses is tossed to the fish from one of the windows and the other window is used to observe the tuna. Observation windows cut into the side of the tanks and covered by protective huts also allow undetected observation of the tuna. A portable keyboard connected to a 20-channel event recorder in the tower is used in the hut to record behavioral data.

basic understanding of the behavior and sensory capabilities of tunas should be useful in the future design of fishing gear and fishing methods and in locating tuna.

To determine how well tunas can see, studies were conducted on their visual acuity (the ability to see clearly the fine details of objects). Of three tunas tested, it was determined that yellowfin tuna could see better than skipjack tuna, and the latter better than kawakawa. Further experiments on the optical system of restrained tuna showed that they are probably color blind and are most sensitive to blue light.



The facilities at Kewalo made it possible to closely observe captive fish and produced the first high-speed movies of swimming kawakawa. The analysis of the film provided intimate details of swimming speed, tail beat rates, body postures and flexures, and how the changing positions of fins and finlets provide drag reduction features. It was determined that the tail provided nearly 100% of the forward thrust and that the fish attained burst speeds of twice that of nonscombrid fish. The line drawing shown here was traced from successive ciné frames (camera speed 100 frames per sec) for one complete caudal fin beat cycle of a kawakawa. The swimming speed of this fish was 8.2 body lengths per sec which was produced by a tail beat frequency of 14.3 tail beats per sec.



To measure tuna's reaction to various sensory stimuli, an observer must be able to detect the fish's response to these stimuli. It was found that tunas can be trained to perform a specific act in response to stimuli if they were rewarded. To measure how well they can see, tunas were trained to respond differently to vertical and horizontal bars that were projected onto an underwater screen by giving rewards (food) or punishment (electric shock). These experiments showed that at a constant brightness, a yellowfin tuna sees details of an object better than a skipjack tuna and a skipjack tuna better than a kawakawa.

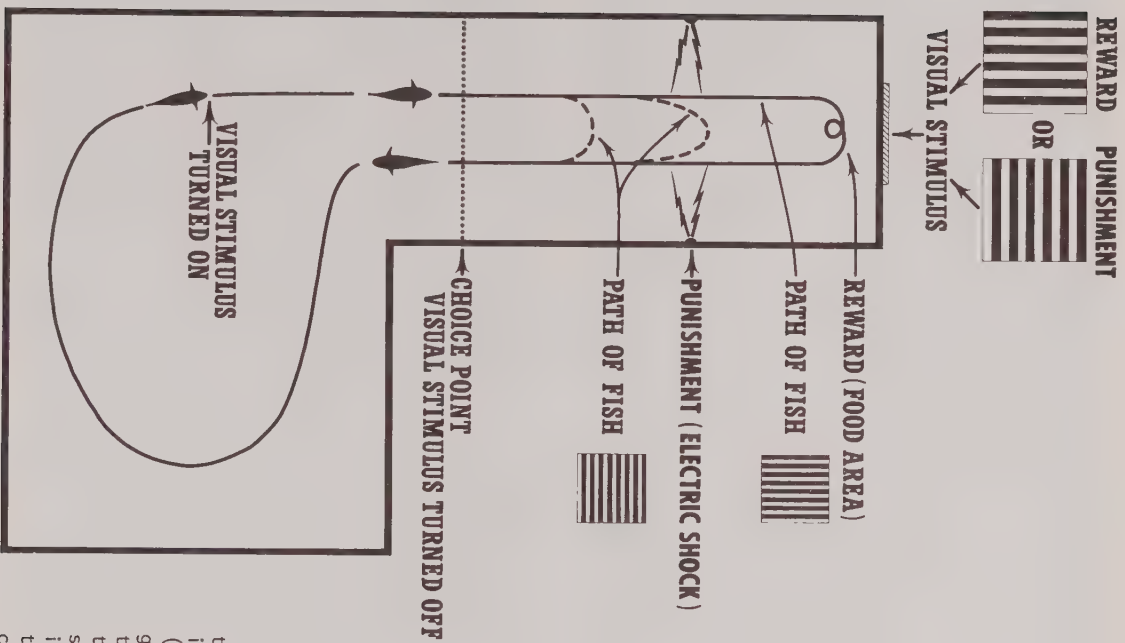
Experiments to define the hearing ability of tunas made it possible to construct a hearing curve for a tuna, the first ever for a scombrid, and to determine their auditory thresholds (the lowest level of sound that can be heard at a specific frequency). It was determined that the hearing range of yellowfin tuna is from about 200-2,000 Hz and that its hearing is most acute at 500 Hz.

Our experiments showed that tunas have a highly developed sense of smell. When a liter (1.06 qt) of water in which a small fish (a smelt weighing 10 g or 0.4 oz) had been dipped for 10 sec was introduced, a strong response was elicited from a school of kawakawa in the tank. It should be noted that the response was elicited even though the rinse water was further diluted by its introduction through the inflow water system. A study of the morphological structure of the nares (nose) of tunas revealed that they can "sniff" water. Each jaw movement of a tuna produces a pumping action that forces water past rosettes in the nares. Observations on fish in captivity showed this action to be continuous.

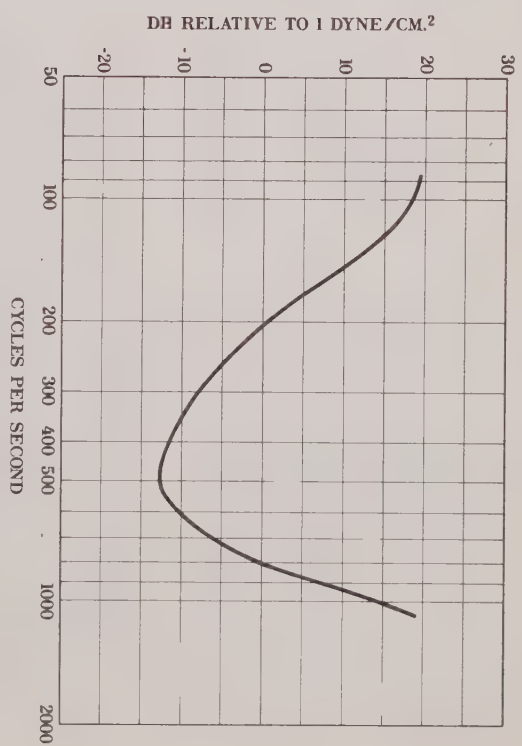
As the techniques to capture, transport, and maintain tunas improved the number of live tunas available for experimental purposes increased proportionately. This made it possible to increase the variety of behavioral and physiological studies such as those on the feeding and digestive rates of tunas. Food or forage organisms usually are not homogeneously distributed in the ocean but are found in patchy concentrations in space and time. Consequently, tunas and other oceanic apex predators exist in a "feast or famine" situation and the periods between feedings may be long. And knowledge of the digestive and feeding rates of fishes existing in such environments as tunas can be of practical use to commercial fishermen.

In this photograph a kawakawa is making an aggressive move towards a school of nehu in a shoreside research tank. Kawakawa has proved to be a good laboratory research animal and is readily available in Hawaiian waters.

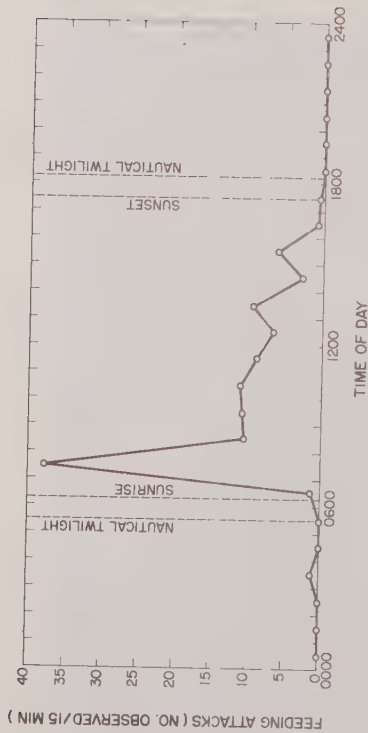




This diagram illustrates the experimental method used to determine the visual acuity of tunas. The method involves training a fish to respond to a visual stimulus (horizontal or vertical stripes), projected on an opal glass plate placed against a tank window. The fish is trained so that when the stripes are vertical it swims down the tank to a food-drop area where it is rewarded; when the stripes are horizontal the fish is trained to turn before it reaches the food-drop area and return to the far end of the tank. If the fish fails to turn it receives an electrical shock.



Experiments to determine the hearing ability of tunas were conducted in a pool specially constructed to insulate the fish from outside sounds and electronic interference. The test fish were first trained to recognize a pure "white" sound and then to react to the sound stimulus by swimming through a maze for a reward. The yellowfin tuna best hears sounds that are near 500 Hz as shown by the dip at that frequency in the hearing curve. Sounds near this frequency are common in the ocean, as for example, the sound produced by the swimming of a school of small fish.



The changes in the feeding activity of kawakawa during a 24-h period as shown in this graph is typical for all tunas. When tunas in captivity were provided with a constant supply of food, feeding motivation was highest at early morning followed by a rapid decrease through noon and two smaller peaks at midafternoon. They showed no attempts to feed at night. This behavior is consistent with the high consumption and digestion of tunas which is from two to five times faster than that of other fish. When tunas are fed continuously, an equivalent of 15% of body weight or two times their stomach volume is eaten. The drive to attack prey is dependent on the amount of food in the stomach. Intense feeding always occurs in the morning when the stomach is empty. However, the stomach is not filled to capacity at the first feeding frenzy and the fish feeds throughout the day. Feeding slows when the stomach is 80% filled.

Upon swimming into an odor cloud of prey or other food items, tunas will typically increase their swimming speed, break the school swimming formation, and display the various color patterns associated with feeding. Kawakawa (pictured) display ventral spots and dorsal stripes; skipjack tuna exhibit lateral vertical bars and a dorsal white stripe and yellowfin tuna show the same color pattern as skipjack tuna plus a dark dorsal coloration.



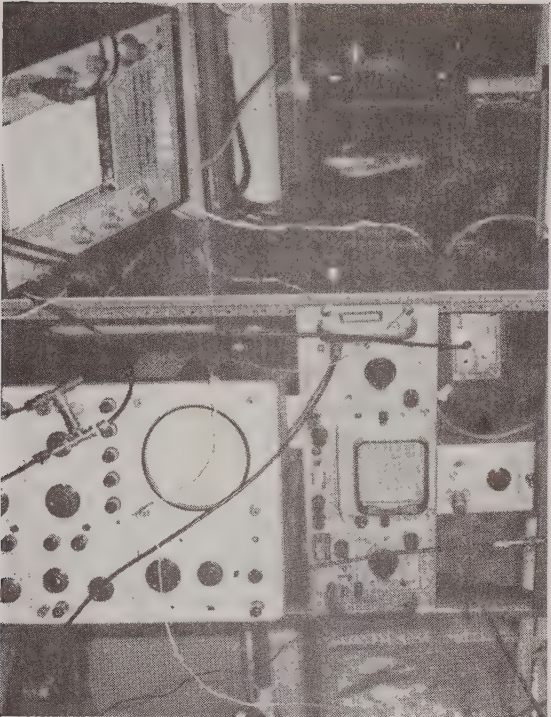
Present Work

Current work at the Kewalo Research Facility includes an effort to determine a model of the energy requirements of skipjack tuna. Such a model will enable scientists to better explain and predict the distribution of the various species of tunas by answering questions such as, what are the limiting environmental conditions in the apparently energy-poor pelagic tropical seas for active fishes like the tunas to thrive in, and what are the dimensions of the tunas' apparent ability to conserve heat and thermoregulate. Already, much of the data collected over the past two decades have been used in the model and the preliminary results indicate that the growth rate of fish less than 11.8 kg (26 lb) is governed by food consumption while growth rate of fish larger than 15.0 kg (33 lb) is limited by the biological demands of activity and metabolism. Laboratory experiments have indicated that the distribution of small fish is dependent on the availability of food and the distribution of large fish is dependent on environmental conditions, of which temperature plays a major role.

Current behavioral and physiological studies include work to test the hypothesis that a tuna will recognize a "food gradient" and position itself in the densest portion of the gradient. To do this a doughnut-shaped tank which has instrumentation to detect if the fish is swimming clockwise or counterclockwise was constructed. Each lap that the fish swims would advance or reverse a looped tape which determines frequency of food presentation ranging from a high to a low rate.

Tests to determine various physiological functions of a quiescent fish are accomplished by restraining a fish in a cradle. The fish is kept alive by forcing aerated water past its gills (photo 1).

An electrode is placed in the brain and the fish's reactions to various stimuli are then monitored visually on an oscilloscope and graphically on a recorder. This technique has been used to determine the reactions of tunas to a range of colors, odors, and muscle stimuli (photo 2).



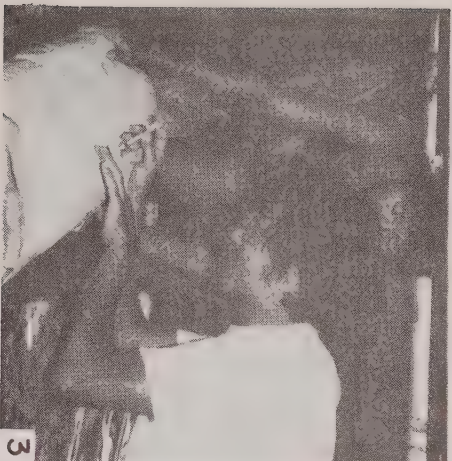
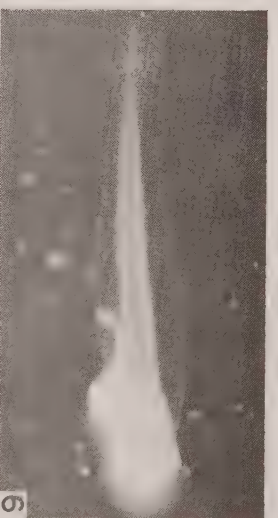
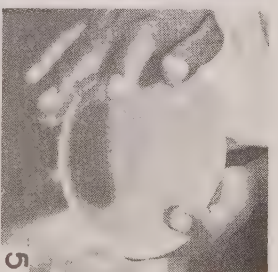
This makes it possible for the fish to remain in the densest portion of the "food gradient" by continually reversing itself once it had discovered a change in the rate of food presentation from high to low. As expected, the fish altered its swimming pattern to spend a higher proportion of its time in the high feeding frequency area.

Recent studies also showed that tunas have a remarkable ability to maintain a higher body temperature than the temperature of the water in which they swim. This is made possible by a heat exchanger that retains the heat produced by metabolic activity within the core of the body whereas in most other fishes all excess metabolic heat is lost at the gills.

As a predator, this ability to maintain an elevated body temperature gives the tuna an extreme advantage over other fishes in that it allows the tuna to operate at higher activity levels. Depending on the activity and size of the fish, maximum excess body temperature can range from 8° to 21°C.

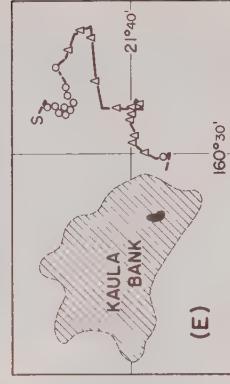
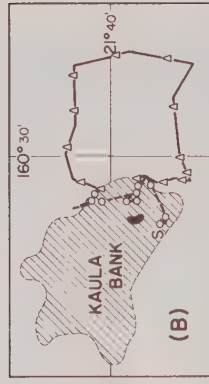
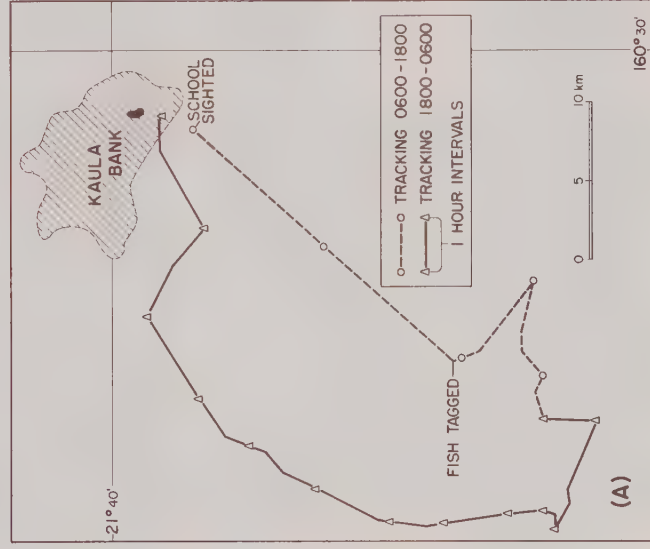
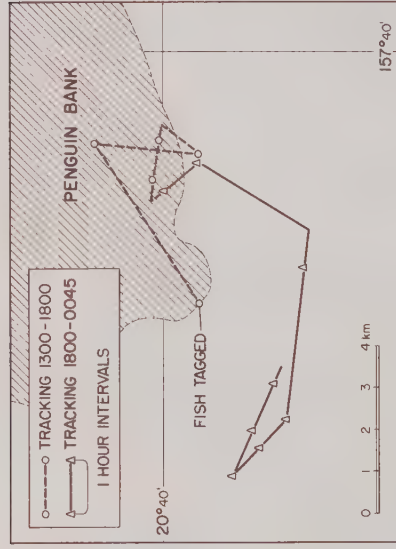
Two new experiments have been designed to determine tunas' ability to perceive changes in water temperature. One experiment makes use of the observation that the heart beat rate of a restrained tuna will slow down when the fish is presented with an external stimulus such as a change in water temperature. In the other experiment a free swimming fish is rewarded with food each time it is able to recognize a temperature difference when water from a spigot is added to the tank. In the restrained fish a temperature change of 1°C elicited a response. The free swimming fish perceived a temperature difference of 0.1°C.

The large accumulation of knowledge on the effects of temperature on the physiology of tunas allowed work to continue on more sophisticated experiments such as those to determine whether tunas can physiologically or behaviorally thermoregulate. The first evidence of physiological thermoregulation in tunas was obtained in experiments with yellowfin tuna. Yellow-



The first successful attempts at artificially inducing spawning in captive tuna were accomplished at the Kewalo Research Facility. The technique involved a periodic biopsy of the tunas to determine the developmental stage of the eggs in the ovaries. After the eggs attain a critical size, hormone treatments are administered to the fish to induce spawning. In the summer of 1979, kawakawa treated with hormone spawned for the first time in the shoreside holding tanks.

This series of photographs shows a kawakawa being guided into a funneling device to entrap it (photo 1) and then strapped into a "straitjacket" (photo 2). The biopsy or the hormone injection is then effected while the fish is immobilized in the "straitjacket" (photo 3). Within 12 h after the final hormone treatment, the fish were ready to spawn and eggs were stripped from the female (photo 4). The ripe eggs were fertilized with milt which was stripped from a ripe male, and the fertilized eggs were then placed in temperature controlled aquaria to hatch (photo 5). The eggs hatched in about 24 h and the yolk sacs of the larvae were absorbed in about 2 days. At this stage a baby tuna (in this case kawakawa) is forced to fend for itself and forage for food (photo 6).



The Honolulu Laboratory was one of the pioneers in the use of sonic tags to track tuna in the open ocean. Tags are now being developed to transmit biological and environmental data such as muscle activity (heart and tail beat rates), temperature (of the fish and water), and depth, in addition to the usual data on location of the fish.

These figures show the tracks of skipjack tuna tagged with sonic tags near Penguin Bank and Kaula Bank. (Track of tagged skipjack tuna at Kaula Bank: (A) from 1452, August 30, to 0600, August 31; (B) from 0600, August 31, to 0600, September 1; (C) from 0739, September 3, to 0600, September 4; (D) from 0600, September 4, to 0600, September 5; (E) from 0600, September 5, to 0730, September 6.)

These results confirmed for the first time that skipjack tuna are temporarily territorial and remain in a given area for some time in Hawaiian waters. Also of interest is the fish's repeated returns to the same area each morning, which implies that skipjack tuna can navigate and have a sense of time.

fin tuna placed in the doughnut tank were able to alter their body temperature physiologically, or thermoregulate, when the water temperature was changed at 6-h intervals. This ability to physiologically thermoregulate, however, has not been demonstrated as yet in all species of tuna.

The other form of thermoregulation, behavioral thermoregulation, involves a fish's ability to select and remain in water of a preferred temperature range. To test the hypothesis that fish of a given size would gravitate to water of a preferred temperature range and stay there, a special two-tank system was devised. The two tanks, 7,571 liters (2,000 gal) each in capacity, are connected by a short tunnel and contain water differing in temperature. If the fish swam from the cooler tank to the warmer tank, the temperature of both tanks would rise. Conversely, if the fish swam from the warmer tank to the cooler tank, the temperature of both tanks would fall. In this way, the fish could control its environmental temperature. These data will provide clues to the preferred temperature range of tunas in the ocean and provide valuable information to commercial fishermen.

Relation with University of Hawaii

The Honolulu Laboratory through its Kewalo Research Facility (and in other ways) maintains a special relationship with the University of Hawaii. There is free dialogue and exchange of information among scientists in the University's Department of Zoology, Physiology, and Biochemistry and the Kewalo Research Facility. The Honolulu Laboratory has provided part-time employment for University of Hawaii undergraduates and support for master's and doctor's degree candidates by providing laboratory space, experimental tuna, and monetary grants. Laboratory scientists have also served on graduate student theses committees. These activities have provided enrichment to the mutual benefit of the University of Hawaii and the Honolulu Laboratory.

BASE FOR RESEARCH VESSELS

The Kewalo Research Facility has also served as the base for research vessels operated by the Honolulu Laboratory. At one time or another, the research vessels Hugh M. Smith and Charles H. Gilbert have docked at the shoreline facilities of the Kewalo Research Facility in the placid waters of Kewalo Basin. Presently, this facility is the home base of the NOAA vessel Townsend Cromwell, which has been assigned to the Honolulu Laboratory for fishery related work in the central Pacific Ocean. A few of the scientific achievements resulting directly from research cruises of vessels operated by the Honolulu Laboratory include:

- The discovery and delineation of the easterly flowing Equatorial Undercurrent (Cromwell Current). Its discovery solved one of the major oceanographic puzzles of our time, the great imbalance of the amount of water flowing westward in the Pacific Ocean as compared to the amount flowing to the east.
- The discovery of a concentration of large, deep-swimming tunas in an equatorial band and determining their relationship to the oceanographic and meteorological features of the Pacific Ocean.
- The preparation of an atlas of the oceanography of the central Pacific Ocean. This description provides basic environmental information of the world of the pelagic fishes, information that is essential to the exploratory and developmental stages of a fishery.

Currently, the Townsend Cromwell is deeply involved in a 5-yr study of the fishery and other biological resources of the Northwestern Hawaiian Islands. The study is being conducted under the provisions of an agreement for a Cooperative Study for the Assessment of the Living Resources of the Northwestern



Hawaiian Islands involving the National Marine Fisheries Service (Honolulu Laboratory), the U.S. Fish and Wildlife Service, and the State of Hawaii (Hawaii Division of Fish and Game and various departments of the University of Hawaii). The Cromwell serves as the primary research platform for this study.

This research program has already provided payoffs in the form of the discovery of valuable spiny lobster and demersal fish resources in the Northwestern Hawaiian Islands. As a result of this discovery, a small fishery for spiny lobsters has developed. With proper management, the Northwestern Hawaiian Islands spiny lobster fishery should contribute to the economic well-being of Hawaii for many years to come.

The research activities of the Honolulu Laboratory cover a wide reach of the tropical and subtropical Pacific Ocean. From 1950 to the present, research vessels of the Honolulu Laboratory sailed over 1 million nautical miles on oceanographic and fishery cruises. Currently, the 48.2 m (158-ft) NOAA vessel Townsend Cromwell is under assignment to the Honolulu Laboratory for its use. In the past the Honolulu Laboratory operated the Henry O'Malley, John R. Manning, Hugh M. Smith, and the Charles H. Gilbert.

APPENDIX 1

List of Visiting Investigators

<u>Investigator</u>	<u>Affiliation</u>	<u>Specialty</u>
DR. JELLE ATEMA	Marine Biological Laboratory Boston University Woods Hole, Massachusetts	Olfaction
DR. JOHN E. BARDACH	Resources Systems Institute East-West Center Honolulu, Hawaii	Olfaction
DR. GRANT R. BARTLETT	Laboratory of Comparative Biochemistry San Diego, California	Blood biochemistry
DR. WILLIAM P. BRAKER	John G. Shedd Aquarium Chicago, Illinois	Aquarist
DR. RICHARD W. BRILL	Department of Zoology University of British Columbia Vancouver, B.C., Canada	Thermal and muscle physiology
DR. PHYLLIS H. CAHN	Department of Zoology Stern College for Women Yeshiva University New York, New York	Behavior
DR. FRANCIS G. CAREY	Woods Hole Oceanographic Institution Woods Hole, Massachusetts	Thermal physiology

<u>Investigator</u>	<u>Affiliation</u>	<u>Specialty</u>
DR. JEAN L. CRAMER	Department of Animal Sciences University of Hawaii Honolulu, Hawaii	Thermal physiology
DR. F. E. J. FRY	Department of Zoology University of Toronto Toronto, Ontario, Canada	Thermal physiology
DR. MALCOLM S. GORDON	Department of Biology University of California Los Angeles, California	Muscle physiology
DR. MICHAEL GUPPY	Department of Zoology University of British Columbia Vancouver, B.C., Canada	Muscle biochemistry
DR. ISAO HANYU	Laboratory of Fish Physiology University of Tokyo Tokyo, Japan	Visual perception
DR. FRANCOIS HAVARD-DUCLOIS	Centre National pour L'Exploitation des Oceans Brest, France	Olfaction
DR. PETER W. HOCHACHKA	Department of Zoology University of British Columbia Vancouver, B.C., Canada	Muscle biochemistry
KIM HOLLAND	Monell Chemical Senses Center University of Pennsylvania Philadelphia, Pennsylvania	Olfaction

<u>Investigator</u>	<u>Affiliation</u>	<u>Specialty</u>
DR. C. S. HOLLING	Institute of Animal Resource Ecology University of British Columbia Vancouver, B.C., Canada	Behavior
DR. WILLIAM C. HULBERT	Department of Zoology University of British Columbia Vancouver, B.C., Canada	Muscle biochemistry
WALTER N. IKEHARA	Hawaii Institute of Marine Biology University of Hawaii Kaneohe, Hawaii	Olfaction
DR. JOHN W. KANWISHER	Woods Hole Oceanographic Institution Woods Hole, Massachusetts	Physiology, tag design
DR. CALVIN M. KAYA	Department of Zoology Montana State University Bozeman, Montana	Endocrine physiology
DR. JAMES F. KITCHELL	Department of Limnology University of Wisconsin Madison, Wisconsin	Bioenergetics
DR. JOHN J. MAGNUSON	Department of Limnology University of Wisconsin Madison, Wisconsin	Thermal physiology
MICHAEL A. MCCOY	Micronesian Maritime Authority Kolonia, Ponape Eastern Caroline Islands	Turtle behavior

<u>Investigator</u>	<u>Affiliation</u>	<u>Specialty</u>
DR. JOHN M. MILLER	Department of Zoology University of North Carolina Raleigh, North Carolina	Larval ecology
ELIZABETH A. MONCKTON	Department of Zoology University of Hawaii Honolulu, Hawaii	Behavior
DR. BARRY S. MUIR	Marine Ecology Laboratory Bedford Institute of Oceanography Dartmouth, Nova Scotia, Canada	Physiology
DR. A. EARL MURCHISON	Naval Undersea Center Kailua-Kona, Hawaii	Behavior
DR. CLAUDE M. NAGAMINE	Institute of Marine Resources University of California Davis, California	Endocrine physiology
DR. WILLIAM H. NEILL	Department of Wildlife and Fisheries Sciences Texas A&M University College Station, Texas	Thermal physiology
DR. ARTHUR J. NIIMI	Canada Centre for Inland Waters Burlington, Ontario, Canada	Metabolism
DR. HIROSHI NIWA	Department of Fisheries Nagoya University Nagoya, Japan	Visual perception

<u>Investigator</u>	<u>Affiliation</u>	<u>Specialty</u>
DR. ELMER R. NOBLE	Department of Biological Sciences University of California Santa Barbara, California	Ectoparasites
LINDA M. PAUL	Department of Zoology University of Hawaii Honolulu, Hawaii	Lobster behavior
DR. DOUGLAS G. PINCOCK	Department of Electrical Engineering University of New Brunswick Fredericton, New Brunswick, Canada	Tag design
DR. WARREN P. PORTER	Laboratory of Limnology University of Wisconsin Madison, Wisconsin	Bioenergetics
DR. JOHN H. PRESCOTT	Oceanarium, Inc. Palos Verdes Estates, California	Courtship behavior
DR. MARTIN D. RAYNER	Pacific Biomedical Research Center University of Hawaii Honolulu, Hawaii	Muscle physiology
DR. TERENCE A. ROGERS	John A. Burns School of Medicine University of Hawaii Honolulu, Hawaii	Muscle and blood biochemistry
DR. BRYANT T. SATHER	Department of Zoology and Physiology Rutgers University Newark, New Jersey	Muscle and blood biochemistry

<u>Investigator</u>	<u>Affiliation</u>	<u>Specialty</u>
DR. EDWARD D. SCURA	Aquatic Farms Kahaluu, Hawaii	Aquaculture
DR. GARY D. SHARP	Inter-American Tropical Tuna Commission La Jolla, California	Thermal physiology
SHERRY STEFFEL	Laboratory of Limnology University of Wisconsin Madison, Wisconsin	Thermal physiology
DR. E. DON STEVENS	Department of Zoology University of Guelph Guelph, Ontario, Canada	Thermal physiology
LEN STUTTMAN	Stuttman Productions East Lansing, Michigan	Television production
DR. E. E. SUCKLING	Downstate Medical Center State University of New York Brooklyn, New York	Neural physiology
DR. J. A. SUCKLING	Department of Zoology Hunter College of the City University of New York New York, New York	Neural physiology
DR. TAMOTSU TAMURA	Agriculture Fisheries Laboratory Nagoya University Nagoya, Japan	Visual perception

<u>Investigator</u>	<u>Affiliation</u>	<u>Specialty</u>
DR. VLADIMIR WALTERS	Department of Zoology University of California Los Angeles, California	Locomotion
DR. DANIEL WEIHS	Department of Aeronautical Engineering Technion-Israel Institute of Technology Haifa, Israel	Hydrodynamics
DR. THEODORE Y. WU	Department of Engineering California Institute of Technology Pasadena, California	Hydrodynamics
MINATO YASUI	Shizuoka Prefectural Fisheries Experimental Station Yaizu, Shizuoka, Japan	Thermal physiology

APPENDIX 2

List of Scientific Publications and Manuscripts Resulting from Research at the Kewalo Research Facility

- ATEMA, J., K. HOLLAND, and W. IKEHARA.
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Running head:

The Cost of Information Seeking in the Optimal Management
of Random Renewable Resources

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Key words:

ABSTRACT

Papers on the management of randomly varying renewable resources have been concerned with uncertainty in the population dynamics. Optimal management regimes in these circumstances depend on the population size, which usually only can be obtained at a large cost. In this paper, algorithms are discussed which allow either for a delay in obtaining the population size, or N years to elapse between population estimates. The algorithms are applied to a model of salmon runs and to an anchovy growth model. In each instance, consistent information delay is found to be costly, while frequent surveys are costly if there is no real risk of depletion. These results raise questions as to the traditionally held view on the value of information, and suggest that managers may prefer surveys for reasons other than management policy per se.

Introduction

The treatment of uncertainty when managing fisheries or other renewable resources has been concerned with uncertainty or randomness in the year to year population dynamics (see for example Reed 1974; Walters 1975; Mendelssohn 1976, 1978; Walters and Hilborn 1976; Mendelssohn and Sobel 1979). Policies that maximize the total expected value of a randomly varying population are contingency plans that say if population size x is observed this year, then take harvest action y . Usually, however, observing the population size is costly--either a costly survey is needed to estimate the population size, or else the estimate normally only is available with a delay, but for some cost can be found currently. It appears to be the standard gospel that more information on the status of the population is always good, no matter what the cost expended to obtain the information. In this paper algorithms are discussed which find optimal policies with information delay or surveying costs. The algorithms are applied to a model of anchovy population dynamics (MacCall 1978) and to a model of salmon runs on the Wood River off Bristol Bay (Mathews 1967). The results suggest that in many instances information is costly--more costly than the gain in expected total value possible from increased information.

If there is no absorbing state, that is, no long-term depletion of the stocks possible, or if the catch per unit effort drops off quickly enough when there are low population levels in the stock, then policies can be found to manage the fishery with incomplete information that

performs nearly as well as the best policy available with incomplete information. Only when there is an absorbing state, and catch per unit effort does not drop off at a rate where the stock cannot be depleted, is information valuable.

This suggests that the main motivation for frequent surveys and costly complete information is to avoid any sizable risk of stock depletion. Even if the population dynamics as modeled do not predict depletion, surveys may reflect our uncertainty about the validity of our population dynamics models, and fears about the irreversibility of the process should the stocks ever be depleted.

In either case, our results suggest a need for a closer examination of why and how we collect the data we do, and more importantly, our attitudes towards risk when using this information.

The Models

The anchovy model is described completely in MacCall (1978). Unlike in that paper, we use fishing mortality, not expected catch, as the decision variable, and restrict effort to lie between 0 and 0.2. Fishing mortality of 0.2 produces expected catches over all population sizes slightly greater than the distribution of catches over the last several years. The population dynamics are:

x_t = Biomass in year t ($\times 10^6$)

F_t = Fishing mortality in year t

d = Normal random variable, zero mean, variance = 0.2294

c_t = Catch in year t , a random variable

v_t = Value of catch in year t

α = Discount factor = 0.97

lower case
alpha

then:

$$(2.1) \quad x_{t+1} = x_t e^{-(F_t + 0.8)} + \left(e^d \left(\frac{1}{3.659} + \left(\frac{1}{x_t} - \frac{1}{3.649} \right) 0.695 \right)^{-1} - x_t e^{-0.8} \right) e^{-0.152 F_t}$$

catch in period t is:

$$(2.2) \quad c_t = \frac{F_t}{F_t + 0.8} x_t \left(1 - e^{-(F_t + 0.8)} \right) + 0.647 \left(e^d \left(\frac{3.649 x_t}{0.190 + 0.305 x_t} \right) - x_t e^{-0.8} \right) \\ \cdot \left(\frac{0.76 F_t}{0.76 F_t + 0.8} \left(1 - e^{-(0.152 F_t + 0.16)} \right) \right)$$

and the value of the catch c_t is (Huppert et al. 1978):

$$(2.3) \quad v(c_t, x_t) = (59.67 \times c_t) - (1.8953 \times 10^{-5} \times c_t^2) - (10,315 \times c_t \times x_t^{-0.4}) .$$

The goal is to:

$$\text{maximize } E \sum_{t=1}^{\infty} \alpha^{t-1} v(c_t, x_t)$$

$$(2.4) \quad \text{s.t. } 0 \leq F_t \leq 0.2$$

The population dynamics for the salmon model are (Mathews 1967):

x_t = Number of recruits in year t

z_t = Number harvested in year t

$y_t = x_t - z_t$ = Number of spawners in period t

d = Normal random variable, zero mean, variance = 0.2098

α = Discount factor = 0.97

Then:

$$(2.5) \quad x_{t+1} = (e^d) (4.077y_t) \exp\{-0.800y_t\}$$

and it is desired to:

$$(2.6) \quad \begin{aligned} &\text{maximize } E \sum_{t=1}^{\infty} \alpha^{t-1} (x_t - y_t) \\ &\text{s.t.} \quad 0 \leq y_t \leq x_t. \end{aligned}$$

Since fishing mortality is a rate, and can be defined independently of the population size, the anchovy model is sensible as defined in (2.1) - (2.4) even when the present population size is not known with certainty. The same is not true for the salmon model, since if by chance $z_t > x_t$, the statement "harvest z_t " has no meaning. In what follows, it is assumed that z_t is a catch quota each year, and that the actual catch is minimum (x_t, z_t) . Then substitute $x_t - \min(x_t, z_t)$ for y_t in (2.5), and the model is sensible for situations where the number of recruits are not known with certainty.

The assumption that the entire stock could be depleted in a single season is somewhat unrealistic. Even with a large quota during years of low population sizes, it would be expected that catch per unit effort could decrease sharply, so that during any single year the stock would not be reduced greatly if population levels are low. However, two justifications are possible for this assumption. Firstly, the absorbing state can be thought of as all population levels such that fishing would be impractical for many years. Inclusion of an absorbing state allows us to approximate the observed behavior of populations that have been harvested to depletion over a period of years. Secondly, by comparing results with and without the absorbing state, we can see how critical the risk of depletion is to the analysis.

Algorithms and Results

The two algorithms used are based on the work of Sondik (1971, 1978) on partially observed Markov decision problems. The key is to use what information we do know about the population to redefine our state in such a way that transition probabilities for the transformed states can be defined. When there is information delay, what is known is the population size last year and the action taken last year. This is known every period, and with some fiddling (2.1) or (2.5) can be redefined for this definition of a state. Details of this specialization of Sondik's algorithm can be found in Brooks and Leondes (1972).

When we go N years without a survey ($N = 0$ implies survey every year, the completely observed problem), sufficient information is contained in a probability distribution, the probability of any given population size this period. This also can be readily computed from (2.1) and (2.5). See Sondik and Mendelssohn (1979) for details of the algorithm.

When $N > 0$, it is necessary to provide an $N + 1$ year contingency plan, that says if x is the population size at the last survey, then for the next $N + 1$ years (including the survey year) take the specified harvest action.

Let $f(i)$ be the optimal expected value when starting with population size i in the completely observed model. Let $f_0(i)$ be the optimal expected value in the surveying year, when we will go N years without a survey, and population size i is the estimated population size. And finally, let $f(i, a)$ be the expected value for the transformed state with information delay.

For computational purposes, each model was discretized. The anchovy model was discretized on a grid of 25 population sizes and 26 fishing mortalities (including zero), while the salmon model was discretized on a grid of 26 population sizes (including zero) and 26 possible quotas.

Fig. 1 Figures 1(a)-(c) give an optimal policy for the anchovy model with $N = 0, 1, 2, 3$. The lines are linear interpolations between the calculated policies at the grid points. The figures compare policies based on how many years have elapsed since a survey was performed. Figure 2 shows an optimal policy (with linear interpolation) for the anchovy model with time delay.

Fig. 3

Figure 3 shows the four optimal quotas for the salmon model when we go 3 years without a survey ($N = 3$), and compares it with the optimal policy for the completely observed problem. An optimal policy for the salmon model with information delays is not easily graphed, but never allows a quota greater than 0.84.

As a measure of the cost of the information, we use two measures throughout, though there are other measures which are both reasonable and possible. The cost of going N years without a survey, compared to going $n < N$ years without a survey is defined as:

b zero

$$(3.1) \quad \text{DIFF} = \text{maximum} \left\{ f_0^n(i) - f_0^N(i) \right\}$$

The cost of the information lag, compared to no information lag, can be measured by:

$$(3.2) \quad \text{CDIFF} = \text{maximum}_i \left\{ f(i) - \text{minimum}_{\substack{\text{(harvest)} \\ \text{(action)}}} f(i, a) \right\}$$

Table 1
Table 2

These values are tabulated in Table 1 for the anchovy model and in Table 2 for the salmon model.

Discussion

To determine the overall value of surveying or not, it is necessary, to include the costs due to surveying or making a current rather than delayed population estimate. Suppose a survey costs C dollars a year,

and the cost of no delay is D dollars a year. Then for a discount factor α , the total cost over an infinite horizon of surveying every year is $C/1-\alpha$, and the total cost over an infinite horizon for current population estimates is $D/1-\alpha$. In practice, C or D may be difficult to determine, since, for example, the survey that obtains population estimates for management may also provide better estimates of the transition functions and other valuable scientific information.

However, suppose we always go 1 year without a survey. Then the total surveying cost is $C/1-\alpha^2$, and the savings is $\alpha C/(1-\alpha^2)$. Therefore, surveying every is preferable only if:

$$(3.3) \quad [1 - \alpha^2/\alpha] \cdot \text{DIFF} > C$$

The equivalent formula for 2 years without a survey is:

$$(3.4) \quad [(1 - \alpha^3/\alpha(1 + \alpha))] \cdot \text{DIFF} > C$$

and for 3 years without a survey:

$$(3.5) \quad [(1 - \alpha^4/\alpha(1 + \alpha + \alpha^2))] \cdot \text{DIFF} > C$$

Similarly, current population estimates are desirable only if:

$$(3.6) \quad (1 - \alpha) \cdot \text{CDIFF} > D$$

Both DIFF and CDIFF in (3.3)-(3.6) can be determined independently of C or D. Given this value, and the value of α , the decisionmaker can decide whether more information is worth the cost.

As examples, for the anchovy model, (3.3)-(3.5) become for $\alpha = 0.97$:

$$(0.0609) \cdot (0.0) > C$$

$$(0.0457) \cdot (0.50482) > C$$

$$(0.0406) \cdot (0.7501) > C$$

The cost of a survey would have to be vanishingly small to make it preferable to survey every year compared to surveying every other year, 2 years without surveying is preferred to surveying every year as long as the cost of a survey is greater than \$23,070, and 3 years without a survey is preferable to surveying every year if the cost of the survey is greater than \$30,454. Two years without a survey is preferred to 1 year without a survey if the survey cost is greater than \$30,744, and 3 years is preferred if the survey cost is greater than \$34,280.

Paying for timely information is preferable only if this costs less than \$219,548 per year.

For the salmon model, the cost of a survey must be less than the value of a discounted harvest of 797,404 for it to be preferable to survey every year instead of going 3 years without a survey. This is roughly 70% of the average yearly harvest when surveying every year. Current information is worthwhile if the total discounted cost is less than a total discounted harvest of 787,020.

These results can be explained more fully by carefully examining both the models and the optimal policies. For the anchovy model, note that the transistion (2.1) is composed of a deterministic exponential mortality on standing biomass, and a random term on recruitment, which depends only on the biomass at the beginning of the period before harvesting has started. Within a year, the discounted biomass of one unit of standing biomass with no fishing mortality and independent of recruitment, is 0.4358. After 2 years, its discounted biomass is 0.19. This suggests that the problem is really a 2-, perhaps a 3-year problem. This observation is born out by noticing that for $N = 2$ and $N = 3$, the same policies are optimal at 0, 1, and 2 years after the survey.

Moreover, the completely observed optimal policy ($N = 0$) has broad ranges of population sizes over which an optimal policy is the same. If we do not survey next year, we do not know the population size, but with very high probability we do know the policy that would have been chosen if a survey had been taken. If the initial population size is 0.100 and we follow an optimal policy for $N = 0$, then with a 99.9% chance we would have a population size less than 0.700 next year. In the zone 0.100-0.700, an optimal policy for $N = 0$ has only one value, that is $F_t = 0$.

If the initial population size was 2.00 and an optimal policy for $N = 0$ were followed, then with a 95.2% chance the population size next year would be greater than 0.900. The zone 0.900-3.649 has only one value for an optimal policy, $F_t = 0.2$.

The observed loss of value in the salmon model is due to having an absorbing state that can be reached in a short time through harvesting. To see this more clearly, Table 3 and Figure 4 compare the salmon model with and without an absorbing state when $N = 1$, that is an interval of 1 year without a survey. When there is an absorbing state, the minimum positive harvest amount is allowed during the non-survey year. This is because there is sufficient growth in 1 year at all spawner population sizes above 280,000 salmon to insure a harvest of that size the next period. However, when there is no absorbing state in the model, during the non-surveying year an optimal policy is an extremely high quota, since the model explicitly assumes that the population will recover no matter what is done.

For $N = 3$, 3 years without a survey, an optimal policy harvests somewhat more than normal during the survey year to take advantage of the known population size. The next year no harvesting is allowed to allow a buildup of the stocks, and for the final 2 years, a small safe harvest is allowed (Figure 3) on the increased recruit population. This policy coincides with traditional wisdom when there is large risk--allow the stocks to build up and then harvest conservatively.

When there is information delay the situation is similar, but in this instance the actual population size is never known while harvesting occurs. Therefore the risk of depletion is even greater than going 1 year without a survey, in fact, both the loss in value and an optimal policy are similar to that of going 3 years without a survey.

Summary

We have demonstrated that it is possible to include the cost of obtaining information into a stochastic management model of a renewable resource. Numerical results suggest that given an accurate transition function for the population, the gathering of costly information may not be justified by the gains in the total value of the resource. It should be added that the information gathered for one purpose often has several other uses, so that the true cost of obtaining the information may be difficult to determine.

The technique we propose allows the gain in value from obtaining the information to be calculated independently of the cost of obtaining the information. Simple formulas are then constructed which say to the decisionmaker that the information is too costly if it costs more than a specified amount. This allows the decisionmaker to use both subjective and objective information to determine the worth of the increase in information.

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Table 1. Maximum loss of total expected economic value in anchovy
model from not decreasing survey interval ($\times 10^6$).

	Survey every year	One year between surveys	Two years between surveys	Three years between surveys
Survey every year	--			
One year between surveys	0.0*	--		
Two years between surveys	0.50482	0.50482	--	
Three years between surveys	0.7501	0.7501	0.2603	--

*The difference was less than the numerical accuracy of the computer program.

Maximum loss due to information delay = 7.31828.

Table 2. Maximum loss in total expected discounted harvest of
salmon runs ($\times 10^6$).

Loss from delayed information $\geq$ 26.234

Loss from 3 years without a survey = 19.6405

Table 3.--Maximum loss in total expected discounted harvest of salmon runs ($\times 10^6$), with and without an absorbing state.

Results for 1 year without survey	With absorbing state	Without absorbing state
Total loss	11.89683	5.37078
Average loss per year	0.3569	0.1611
Percent of average yearly harvest, surveying every year	31.4%	14.2%
Cost above which survey is not worthwhile	0.724848	0.327229

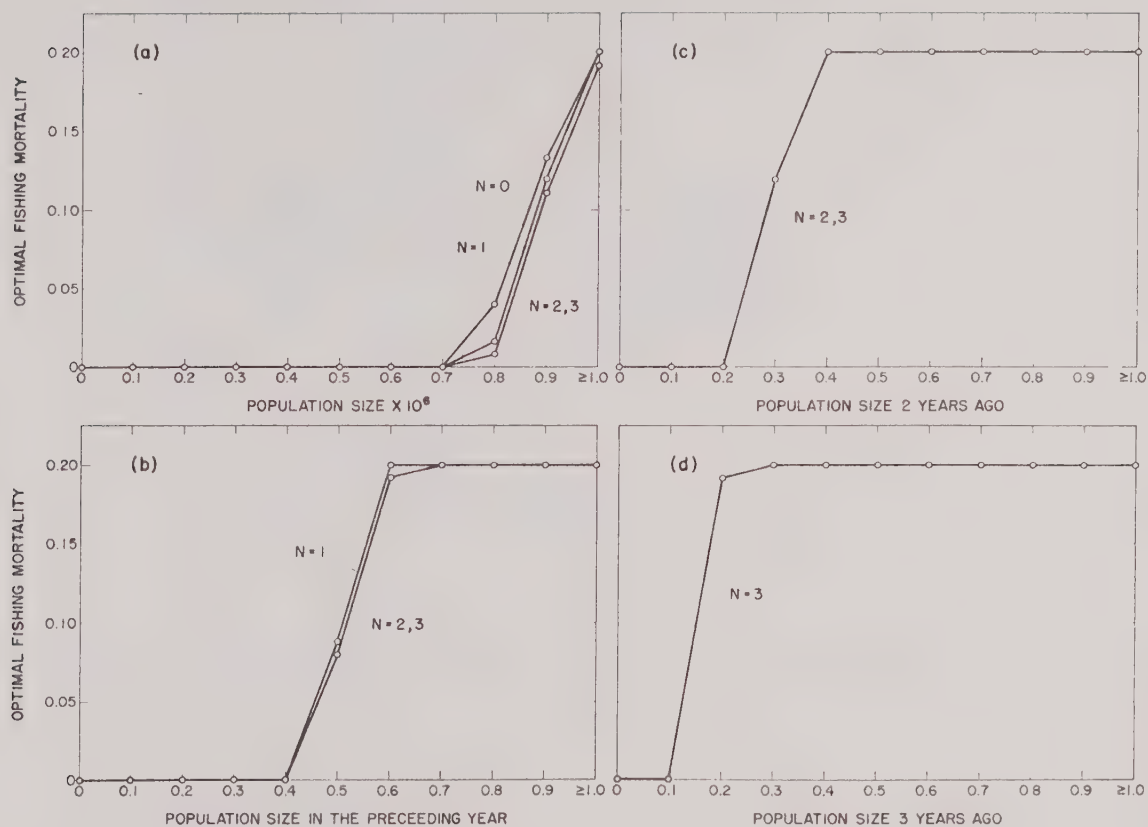


Figure 1.--Optimal policies for the anchovy model at each period,
for 0, 1, 2, and 3 years without a survey.

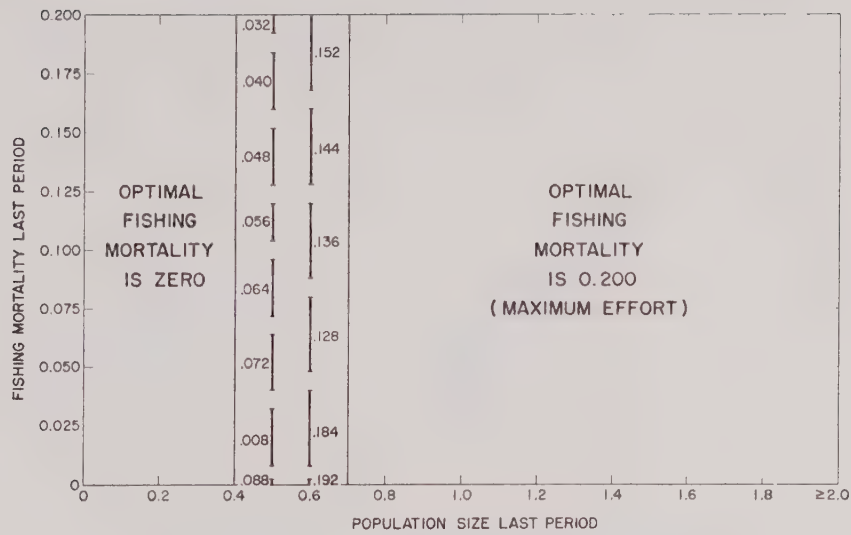


Figure 2.--Optimal policy for the anchovy model with information delay.

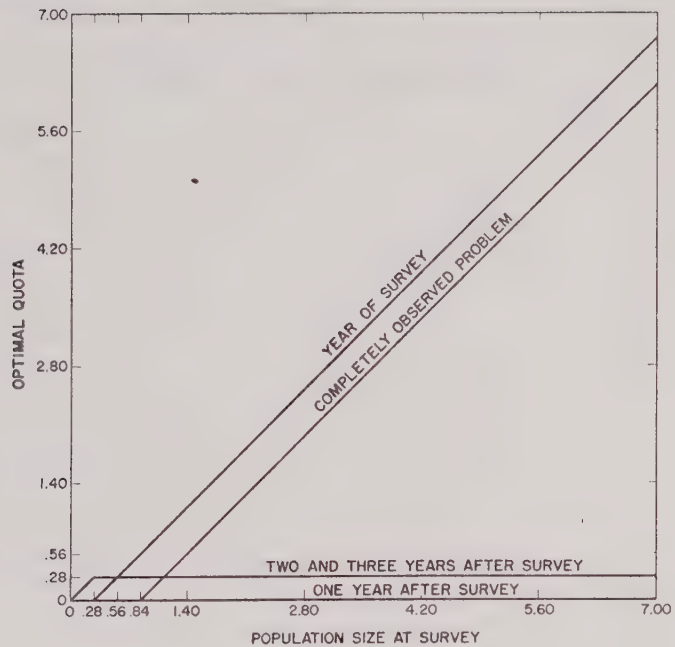


Figure 3.--Optimal policy for the salmon model (with absorbing state), 3 years without a survey.

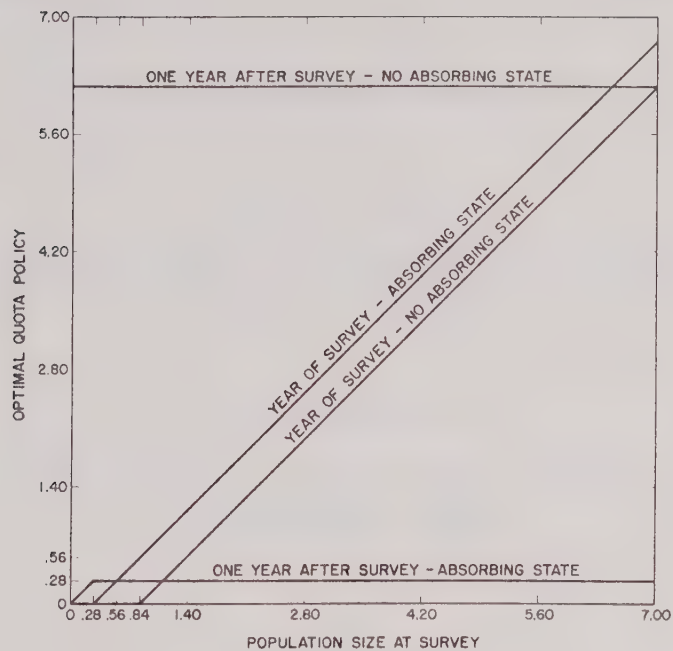


Figure 4.--Optimal policies for the salmon model for $N = 1$,
with and without an absorbing state.

Information Seeking in Markov Decision Processes

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In many decision and control problems the system's state can be observed only at considerable cost. Typical examples include: The control of a population of hypertensives in which the variables of interest are the awareness, attitudes, knowledge, and control status of the population [1], [2], [3]; machine inspection and replacement [4], [5], [6]; and the example which prompted this work, the management of a randomly varying fishery [7], [8], [9]. These problems share the common characteristics of Markovian-like dynamics with incompletely known state information. This paper derives efficient policy and value iteration algorithms for computing optimal control policies for such problems. The major assumptions in the formulation are that the underlying dynamic process is Markovian (discrete time) and that the state dynamics process is obscured between information seeking actions, which we term surveys. We also assume the surveys in general provide perfect information on the state of the process.

The primary problem which motivated this research relates to the management of a fishery resource. In essence, the problem is to outline either the fishing effort or the maximum permissible catch in a time period (1 year). The state of the fishery at a given time can be defined as the number of fish present or more generally, as the weight of the fish present, the biomass. The general relationship is that too large a catch in a period of low biomass can seriously deplete the resource--even eliminate it. The biomass can be accurately measured by surveying each year before the fishing season commences. The problem we address is how frequently should we survey?

This paper derives algorithms for two problems. The first problem is to determine the optimal survey interval s , $s \geq 1$, and the optimal control for the system as a function of some initial state of information. The second more general problem is to derive controls and survey times based on the time since a given state was last observed.

The algorithms are efficient in the sense that they outperform the naive approach to the problem. For a problem with N states and the same A actions per state, a simple approach is to take the s -fold Cartesian product of the action space as the new action space, and redefine the expected one-period reward as the expected reward from choosing any s -vector of actions. This reformulated problem is a completely observed Markov decision process that requires a search over $N \cdot A^s$ alternatives for each iteration of a successive approximation algorithm. The algorithms proposed in this paper require a search over at most $N \cdot A \cdot s$ alternatives and often much fewer alternatives than that. For example, in [10], a problem is solved with 25 states, 26 actions, and $s = 4$. For the naive approach, this would require a search over 11,424,400 alternatives each iteration, while the algorithms of this paper required a search over far fewer than the 2600 alternatives per iteration upper bound.

1. ANALYSIS AND THE BASIC ITERATION ALGORITHM

In this section we analyze the cost of a given policy and derive the value iteration and policy iteration algorithms. We assume the system can be described by an N state discrete time Markov process. Whenever the process is observed perfect information on the state is obtained, but the observations need not be taken each time period. The process is

controlled by choosing one of A alternatives each time period with the a^{th} alternative represented by an $N \times N$ state transition matrix $P(a)$ and a reward vector $\gamma(a)$. The observation or survey process is assumed to take place instantaneously at the beginning of a time period, before a control alternative has been selected for that time period. We consider that the system will be observed every s time units using a survey which costs $C(s)$. Costs are discounted by a discount factor β , $0 \leq \beta < 1$.

A control policy is defined by a sequence of functions $\delta(i, s', \pi)$, $0 \leq s' < s$, $1 \leq i \leq N$, where s' is the number of time units that have elapsed since the last survey was performed, i is the state that was observed at the last survey, and π is the current N -vector of state probabilities just prior to the application of $\delta(i, s', \pi)$. (The vector π is written $\pi = (\pi_1, \pi_2, \dots, \pi_N)$ where π_i is the probability that the dynamic process actually is in state i .) We seek a control policy to maximize the expected discounted rewards of operating the system over an infinite horizon. A control or decision policy for fixed s is denoted by

$$\delta \equiv \left(\delta(0), \dots, \delta(s-1) \right).$$

For a fixed intersurvey interval s the cost of a given policy is developed by defining $f(i, s', \pi)$, $0 \leq s' \leq s$ as the expected discounted reward of operating the system given that s' time units have elapsed since the last survey, that i was the state observed at the last survey and that π is the state probability vector s' time units since the last survey. The functions $f(i, s', \cdot)$ satisfy the following system of equations:

$$f(i, s', \pi) = \pi \gamma \left(\delta(i, s', \pi) \right) + \beta f \left(i, s' + 1, \pi P \left(\delta(i, s', \pi) \right) \right) \\ 0 \leq s' \leq s-1$$

$$f(i, s, \pi) = \pi f(0) - C(s) \quad (1)$$

where $f(0)$ is the column vector $(f(1, 0, e_1), f(2, 0, e_2), \dots, f(N, 0, e_N))$ and e_i is the state probability vector $(0, 0, \dots, 0, 1, 0, \dots, 0)$ with 1 in the i^{th} position representing perfect observation of state i . Note that for a given policy δ the state probability vector π is completely determined by i and s' ; thus equation (1) can be more compactly represented by suppressing the dependence on i as follows:

$$f(s', \pi) = \pi \gamma \left(\delta(s') \right) + \beta f \left(s' + 1, \pi P \left(\delta(s') \right) \right) \quad 0 \leq s' \leq s-1 \\ f(s, \pi) = \pi f(0) - C(s) \quad (2)$$

We note that for any policy δ the functions $\delta(i, s', \pi)$ simplify as follows:

$$\delta(i, 0, e_i) = \delta(i, 0) \\ \delta(i, 1, \pi) = \delta(i, 1, \pi(1, i)) = \delta(i, 1) \text{ where} \quad (3) \\ \pi(1, i) = e_i P \left(\delta(i, 0) \right) \\ \delta(i, 2, \pi) = \delta(i, 2, \pi(2, i)) = \delta(i, 2) \text{ where} \\ \pi(2, i) = \pi(1, i) P \left(\delta(i, 1) \right)$$

$$\begin{array}{ccc} \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \end{array}$$

The state probability vectors $\pi(1, i)$, $\pi(2, i)$, ..., $\pi(s, i)$ are called the descendents of state i under policy δ , and are important to the algorithms to follow. Indeed, with the descendents identified, equation (2) is a linear system easily solved for the column vector $f(0)$. It is straightforward to show that an optimal policy δ^* exists that maximizes $f(s', \pi)$ for all s' by noting that for fixed s the process is a partially observed Markov process with $N \cdot s$ states. Existence follows from [11].

An optimal policy is defined, in general, over all possible states of knowledge at each point in time; however, in fact it is sufficient to consider only those states of knowledge that are descendents of completely observed states. Any other states of knowledge are in effect transient, and once a survey is performed will never reoccur. Thus the problem is reduced from considering N states at time $s' = 0$ and the $s-1$ $(N-1)$ -dimensional simplices of states of knowledge to simply N states at time $s' = 0$ and N (N) -vectors at each of the $s-1$ succeeding time periods between observations. Thus an optimal policy can be defined as that policy $\delta^*(s)$ that maximizes $f(i, 0)$ and $f(i, s', \pi(s', i))$ $1 \leq s' \leq s$, $1 \leq i \leq N$.

The existence of an optimal policy allows us to concentrate on finding an efficient procedure for improving a policy in order to develop a policy iteration algorithm. We proceed by decomposing the functions $f(i, s', \pi)$ into $f(i, s', \pi) = \pi \alpha(i, s')$. From equations (1) and (2) we can show that the column vectors $\alpha(i, s')$ satisfy:

$$\begin{aligned} \alpha(i, s') &= \gamma(\delta(i, s')) + \beta P(\delta(i, s')) \alpha(i, s' + 1) \quad 0 \leq s' \leq s-1 \\ \alpha(i, s) &= f(s, 0) - C(s) \underline{1} \end{aligned} \quad (4)$$

where $\underline{1}$ is a column vector of ones.

We can use the return functions of a given policy δ to find a policy $\hat{\delta}$ that has rewards at least as great as the rewards from δ . This fact is proven in theorem 1 below. Before stating and proving the procedure, we need to examine more closely the function $f(i, s', \pi)$. In general, a given policy defines this function at N points in the space Π , the space of all possible states of knowledge. These N points are the descendants of each state i at time s' . In order to say one policy has an improved expected reward over another policy, we must be able to define $f(i, s', \pi)$ at values of π which are not one of the N descendants of the given policy. Note that for a given policy δ , $f(i, s', \pi) = \pi\alpha(i, s')$ corresponds to the cost of applying policy $\delta(i, s')$, $\delta(i, s' + 1)$, ..., $\delta(i, s-1)$ starting at time s' with state of information π . Clearly, we should choose the sequence $\delta(i, s')$, $\delta(i, s' + 1)$... that maximizes our expected reward. Thus we can let $f(i, s', \pi) = \max_{\ell} \pi\alpha(\ell, s')$. This definition allows $f(i, s', \pi)$ to be well defined over the entire space Π . (A rigorous proof for the sufficiency of this definition can be found in [11].)

We can identify a new policy $\hat{\delta}$ based on δ as follows:

$$\hat{\delta}(i, s) = \underset{a}{\operatorname{argmax}} [\pi(s, i)\gamma(a) + \beta\pi(s, i)P(a)f(0)] \quad (5)$$

$$\hat{\delta}(i, s') = \underset{a}{\operatorname{argmax}} [\pi(s', i)\gamma(a) + \beta \max_{\ell} \pi(s', i)P(a)\hat{\alpha}(\ell, s' + 1)]$$

$$0 \leq s' \leq s - 1$$

where the α 's are defined recursively

$$\hat{\alpha}(i, s) = \gamma(\hat{\delta}(s)) + \beta P(\hat{\delta}(s))f(0)$$

$$\hat{\alpha}(i, s') = \gamma(\hat{\delta}(s')) + \beta P(\hat{\delta}(s'))\hat{\alpha}(\hat{\ell}, s' + 1)$$

where $\hat{\ell}$ achieved the inner maximum in (5).

In essence, a new policy is found for each state and each intersurvey time point. The points $\hat{\pi}(1, i)$, $\hat{\pi}(2, i)$, ..., $\hat{\pi}(s-1, i)$ together with $\hat{\pi}(s, i)$ are the descendants of i for the new policy $\hat{\delta}$. We now prove that $\hat{\delta}$ is an improved policy over δ .

Theorem 1. a) The expected value of following policy $\hat{\delta}(s)$ is greater than or equal to the expected value of following policy $\delta(s)$ having just observed state i . That is,

$$\hat{f}(i, 0) \geq f(i, 0) \quad \text{for each } i$$

b) If $\hat{\delta}$ maximized $f(i, s)$ for all i then $\hat{\delta} = \delta^*$ such that δ^* maximizes $f(i, s', \pi(s', i))$ where $\pi(s', i)$ is the s' -th descendent of i under policy δ^* .

Proof. Let $\bar{f}(i, s', \pi(s', i))$ be the "improved" value after applying (5). At $s' = s$,

$$\begin{aligned} \bar{f}(i, s, \pi(s, i)) - f(i, s, \pi(s, i)) &= \pi(s, i) \left(\gamma(\hat{\delta}(s)) - \gamma(\delta(s)) \right) \\ &\quad + P(\hat{\delta}(s))f(0) - P(\delta(s))f(0) \end{aligned} \quad (6)$$

which is nonnegative since maximums are taken in (5). Suppose for $s' = s, s-1, s-2, \dots, j$ it is true that $\bar{f}(i, s') - f(i, s) \geq 0$ for all states i . Then at $s' = j-1$:

$$\begin{aligned} \bar{f}(i, j-1, \pi(j-1, i)) &= \pi(j-1, i) \gamma(\hat{\delta}(j-1)) + \beta \max_{\ell} \pi(j-1, i) P(\hat{\delta}(j-1)) \hat{\alpha}(\ell, j) \\ &\geq \pi(j-1, i) \gamma(\delta(j-1)) + \beta \max_{\ell} \pi(j-1, i) P(\delta(j-1)) \hat{\alpha}(\ell, j) \end{aligned} \quad (7)$$

Substituting (6) into (7) we have

$$\begin{aligned} \hat{f}(i, s', \hat{\pi}(s', i)) - f(i, s', \hat{\pi}(s', i)) &= \Delta(i, s') \\ &+ \beta [\hat{\pi}(s', i) P(\delta(s')) \alpha(\ell, s' + 1) - \hat{\pi}(s', i) P(\hat{\delta}(s')) \alpha(\hat{\ell}, s' + 1)] \\ &+ \beta \left[\hat{f}(i, s' + 1, \hat{\pi}(s' + 1, i)) - f(i, s' + 1, \hat{\pi}(s', i) P(\delta(s))) \right] \end{aligned} \quad (8)$$

Noting that $f(i, s' + 1, \hat{\pi}(s', i) P(\delta(s))) = \max_{\ell} \hat{\pi}(s', i) P(\delta(s)) \alpha(\ell, s' + 1)$

yields for $0 \leq s' \leq s-1$:

$$\begin{aligned} \hat{f}(i, s', \hat{\pi}(s', i)) - f(i, s', \hat{\pi}(s', i)) &= \Delta(i, s') \\ &+ \beta \left[\hat{f}(i, s' + 1, \hat{\pi}(s' + 1, i)) - f(i, s' + 1, \hat{\pi}(s' + 1, i)) \right] \end{aligned} \quad (9)$$

and for s : $\hat{f}(i, s, \hat{\pi}(s, i)) - f(i, s, \hat{\pi}(s, i)) = \hat{\pi}(s, i) \cdot [\hat{f}(0) - f(0)]$.

Equation (9) and the fact that $\Delta(i, s') \geq 0$ imply that:

$$\hat{f}(i, s', \hat{\pi}(s', i)) - f(i, s', \hat{\pi}(s', i)) \geq 0 \quad 0 \leq s' \leq s-1 \quad (10)$$

Letting $s' = 0$ (for which $\hat{\pi}(0, i) = \pi(0, i) = e_i$) proves part a) of the theorem.

Part b) of theorem guarantees that nonoptimal policies will always be improved. To prove the assertion we assume that δ cannot be improved by (5) but that $\delta^* \neq \delta$ is optimal. Optimality implies that:

$$f^*(i, s', \pi^*(s', i)) \geq f(i, s', \pi^*(s', i)) \quad (11)$$

the last inequality again because (5) implies finding a maximum. By definition, $\pi(j-1, i)P(\delta(j-1)) = \pi(j, i)$. At j , $\hat{\delta}(j)$ was found to have been an improved policy for $\pi(j, i)$. This implies

$$\begin{aligned} \max_{\ell} \pi(j-1, i)P(\delta(j-1))\hat{\alpha}(\ell, j) &\geq \pi(j-1, i)P(\delta(j-1))\alpha(i, s) \\ &= f(i, j, \pi(j, i)) \end{aligned} \quad (8)$$

Combining equations (7) and (8) we have

$$\begin{aligned} \bar{f}(i, j-1, \pi(j-1, i)) &\geq \pi(j-1, i)\gamma(\delta(j-1)) + \beta\pi(j-1, i)P(\delta(j-1))\alpha(i, j) \\ &= f(i, j-1, \pi(j-1, i)) \end{aligned} \quad (9)$$

The inductive proof yields the desired result that $\bar{f}(i, 0) \geq f(i, 0)$ for all states i . The improvement algorithm (5) starts with an initial value $f(0)$, and adds a value equal to the s -period expected reward of policy $\hat{\delta}$. Let $G(i, \hat{\delta})$ be the expected s -period reward when state i is observed at the survey, and policy $\hat{\delta}$ is followed. Then (5) and (9) imply:

$$\bar{f}(i, 0) = G(i, \hat{\delta}) + \beta^s \hat{\pi}(s+1, i)f(0) \quad (10)$$

Define $\Delta(i) = \bar{f}(i, 0) - f(i, 0)$, let $\hat{f}(i, 0)$ be the value of $\hat{\delta}$ calculated in the policy evaluation stage, and let $\Delta f(i) = \hat{f}(i, 0) - f(i, 0)$. Then it follows from standard arguments in Markov decision processes that

$$\Delta f(i) = \Delta(i) + \hat{\pi}(s+1, i)\Delta f \quad (11)$$

The remainder of the proof of parts a) and b) follow as in [

□

Noting that for fixed s the set of all policies is finite, we now have the rudiments for a policy iteration algorithm. In order to determine the optimal survey interval--which may be unbounded--we would compute an optimal policy and its expected return for increasing intervals until increasing the survey interval further decreases the expected rewards for some state i immediately after observation. In using the algorithms summarized in the next section, the optimal policy and/or optimal value functions derived for an interval of length s are used to initialize the iterations for finding an optimal policy and value for an interval of length $s+1$. In practice, to date, only a few iterations are required to find the optimal policy and/or value function for each sampling interval $s > 1$.

2. POLICY AND VALUE ITERATION ALGORITHMS FOR FINDING δ^*

ig. 1 The algorithm to find δ^* for fixed s is summarized in Figure 1. For $C(s) = 0$ and $s = 1$ the algorithm reduces to the standard policy iteration algorithm.

ig. 2 Figure 2 summarizes an equivalent value iteration algorithm. For $C(s) = 0$ and $s = 1$, the algorithm described is Jacobi iterates of successive approximations. The usual upper bounds, as in [12] are still valid, however, the lower bounds given in [12] are not valid except when $C(s) = 0$ and $s = 1$.

3. MAXIMAL INFORMATION ALGORITHM

The algorithms of the preceding section do not make full use of the available information in that they do not allow surveys to occur--if warranted--before the obligatory survey interval s . In this section we relax this restriction, and augment the policy alternative space by a

survey alternative. The survey, if chosen, is assumed to occur immediately following a transition, i.e., at the start of a new time period, and does not consume a time period. If the survey is chosen at the start of a time period in effect two alternatives are chosen: first the survey alternative and then a regular alternative based on the perfectly observed state obtained from the survey. It is straightforward to modify these assumptions to allow for surveys that require a full time period.

We proceed by modifying equation (2) to include the survey alternative. We denote the survey alternative as alternative $A+1$. As above, we assume a survey will be performed following the s^{th} interval unless performed before that time. The cost of a given policy δ for these assumptions is given by (12), where the points $\pi(s', i)$ are the descendants of the policy δ .

For $0 \leq s' \leq s-1$:

$$\begin{aligned} f(i, 0) &= e_i \gamma(\delta(i, 0)) + \beta f(i, 1, \pi(1, i)) \\ f(i, s', \pi(s', 1)) &= \begin{cases} \pi(s', 1) \gamma(\delta(s', 1)) + \beta f(i, s', \pi(s'+1, 1)) & , \delta(i, s') \neq A+1 \\ \pi(s, i) f(0) - C(s), & \delta(i, s') = A+1 \end{cases} \end{aligned} \quad (12)$$

$$f(i, s, \pi(s, i)) = \pi(s, i) f(0) - C(s)$$

By defining $f(i, s', \pi) = \max_{\ell} \pi \alpha(\ell, s')$ as in section 1, we construct the policy improvement algorithm as follows: An improved policy $\hat{\delta}$ is found by

$$\hat{\delta}(i, s) = \operatorname{argmax}_{a, A+1} \begin{cases} \pi(s, i)\gamma(a) + \beta\pi(s, i)P(a)f(0) \\ \pi(s, i)f(0) - c(s) \end{cases} \quad (13)$$

$$\hat{\delta}(i, s') = \operatorname{argmax}_{a, A+1} \begin{cases} \pi(s, i)\gamma(a) + \beta \max_{\ell} \pi(s, i)P(a)\alpha(\ell, s' + 1) \\ \pi(s, i)f(0) - c(s) \end{cases}$$

$$1 \leq s' \leq s - 1$$

where the $\hat{a}$'s are defined recursively as

$$\hat{\alpha}(i, s) = \gamma(\hat{\delta}(s)) + \beta P(\hat{\delta}(s))f(0)$$

$$\hat{\alpha}(i, s') = \gamma(\hat{\delta}(s')) + \beta P(\hat{\delta}(s'))\hat{\alpha}(\hat{\ell}, s' + 1)$$

$$1 \leq s' \leq s - 1$$

where $\hat{\ell}$ achieves the inner maximum in (13).

The improvement algorithm will converge to a possibly suboptimal policy that is to a policy at least optimal for some survey interval $s' < s$. Suppose that a policy is reached that will always survey at an interval s' less than s . Then the states $\pi(i, j)$, $s' < j \leq s$ are transient, in the sense that once a survey is performed, they will never be reached. The algorithm in (13) must be perturbed to consider the possibly transient policies. To do this, at $s' - 1$ an improved policy must be found by searching over all two-period policies, that is:

$$\hat{\delta}(i, s' - 1) = \operatorname{argmax}_{a, A+1} \begin{cases} \pi(s' - 1, i)\gamma(a) + \beta \max_{a', A+1} \pi(s' - 1)P(a)\hat{\alpha}(i, s', a') \\ \pi(s' - 1, i)f(0) - c(s) \end{cases}$$

where $\hat{\alpha}(i, s', a) = \gamma(a') + \beta P(a')\hat{\alpha}(\hat{\ell}, s' + 1)$

The result is a pair of policies $\hat{\delta}(i, s' - 1)$ and $\hat{\delta}(i, s') = a'$. With this perturbation added if the algorithm converges to a policy that will always survey within an interval $s' < s$, the improvement algorithm can be seen to guarantee that nonoptimal actions will be improved, as we now show.

Theorem 2. In the general case in which surveys (perfect state information) are allowed before time period s , the expected value of following the policy $\hat{\delta}$ given in equation (13), having just observed state i , is greater than or equal to the expected cost of following policy δ , i.e.

$$\hat{f}(i, 0) \geq f(i, 0) \text{ for all } i$$

In addition, if $\delta(s)$ cannot be improved, then $\delta = \delta^*$.

Proof: Essentially the same as theorem 1, with the following definition. Assume that $\delta(i, s') = A + 1$. Then nominally $\delta(i, s'')$, $s \geq s'' > s'$ is undefined. We define this alternative to be the $A + 1$ st (survey) as follows: If $\delta(i, s') = A + 1$, then $\delta(i, s'') = A + 1$ for $s \geq s'' \geq s'$. With this definition, $f(i, s'', \pi) = f(i, s', \pi)$ and the proof proceeds as in theorem 1.

figs. 3,4 A policy iteration algorithm and a value iteration algorithm for the maximal information case are described in Figures 3 and 4.

4. AN EXAMPLE

To illustrate the algorithms, we consider Howard's toymaker problem [4], revamped to allow for surveys to provide state information. The original problem has the following parameters:

State i	Alternative a	$P_{ij}(a)$	$\gamma(a, i)$
1. Successful toy	1. No advertising	0.5 0.5	6
	2. Advertising	0.8 0.2	4
2. Unsuccessful toy	1. No research	0.4 0.5	-3
	2. Research	0.7 0.3	-5

We employ a discount rate of $\beta = 0.9$; the optimal solution for the completely observed problem is $\delta(1, 0) = \delta(2, 0) = 2$, $f(1, 0) = 22.2$, $f(2, 0) = 12.3$ with $C(s) = 0$.

To address the problem without perfect information at each time period we expand the alternative space to consider four alternatives including one in which both advertising and research occur.

Alternative a	$P(a)$	$\gamma(a)$
Advertising/ no research	$\begin{bmatrix} 0.8 & 0.2 \\ 0.4 & 0.6 \end{bmatrix}$	$\begin{bmatrix} 4 \\ -5 \end{bmatrix}$
No advertising/ no research	$\begin{bmatrix} 0.5 & 0.5 \\ 0.7 & 0.3 \end{bmatrix}$	$\begin{bmatrix} 4 \\ -5 \end{bmatrix}$
No advertising/ research	$\begin{bmatrix} 0.5 & 0.5 \\ 0.4 & 0.6 \end{bmatrix}$	$\begin{bmatrix} 6 \\ -3 \end{bmatrix}$
Advertising/ research	$\begin{bmatrix} 0.8 & 0.2 \\ 0.7 & 0.3 \end{bmatrix}$	$\begin{bmatrix} 2 \\ -7 \end{bmatrix}$
Survey	--	$-C(s)$

We arbitrarily choose $C(s) = 0.20$, and begin the algorithm with $s = 1$, equivalent to perfect observation each time period at a cost $C(s)$. We begin with $\delta(i, 0) = 1$, $\delta(i, 1) = \text{survey}$ and find that an optimal policy and its returns are as follows:

i	s'	Policy $\delta^*(i, s')$	Return $f^*(i, s')$
1	0	Survey	
1	1		
2	0	Survey	
2	1		

We proceed to $s = 2$ beginning the iteration with an optimal policy for $s = 1$. Then $\delta(i, s') = \delta^*(i, s')$, $s' = 0, 1$ and we set $\delta(i, 2) = \text{survey}$. After iterations the solution is:

i	s'	Policy $\delta^*(i, s')$	Cost $f^*(i, s')$
1	0	Survey	
1	1		
1	2		
2	0	Survey	
2	1		
2	2		

Proceeding to $s = 3$ and starting with $\delta^3(i, s') = \delta^{2*}(i, s')$, $s' = 0, 1, 2$, with $\delta^3(i, 3)$ representing survey, in ___ iterations we find the same optimal cost and control and conclude that $s = 2$ is optimal.

It is illustrative to consider the sensitivity of an optimal policy (and optimal value of s) to changes in $C(s)$. Figure 5 shows these changes. Note that for $C(s) \geq 1.00$ it is optimal not to survey.

5. SUMMARY AND CONCLUSIONS

The algorithms presented in this paper generalize policy iteration to the case of periodic perfect observation of a Markov process. The algorithms are based on an analysis of the process as a partially observable Markov decision process. The resulting algorithms appear to be highly efficient, requiring only a few extra iterations for each stage s .

The policy iteration algorithms have been programmed in APL and have been run interactively on the computer at the National Institute of Health/ a DEC 10) and on the University of Hawaii's IBM 370/158. The value iteration algorithms have been programmed in FORTRAN and have been run on the University of Hawaii's IBM 370/158. Further computational experience with these algorithms on real life fisheries problems are reported in [10]. (Reference to trade names does not imply endorsement by the National Marine Fisheries Service, NOAA.)

Another potential use for these algorithms is in solving machine inspection and replacement problems. The algorithms solve the renewal problem in a straightforward fashion with a minimum of computational effort. More importantly, the algorithm allows the machine inspection and replacement problem to be modeled and solved in more detail than the usual two or three state, two or three action problem. Using the value iteration algorithm, we have solved a 25 state problem with 26 actions per state for $s = 4$ in slightly over 2 minutes of CPU time, including time to compile the program and to calculate from a problem defined on a continuous state space the transition probabilities and reward vector on a discrete grid. A problem this size would be impractical to solve using either the naive approach of forming an equivalent completely observed problem, or else by using the algorithm for a full scale partially observed Markov decision

problem given in [11]. The algorithm can also solve larger problems with less restrictive assumptions than the regenerative stopping algorithm discussed in [

In all the examples we have solved so far, information seeking has been found to be costly. Over a broad range of values of s , little value is added to the expected return function by surveying more frequently, while the surveys themselves have been expensive. Yet decisionmakers appear to still favor frequent surveys. We can speculate two reasons for this. Firstly, managers may be incorrect in their valuation of information. Secondly, the information may be deemed important either to improve the transition probability model, or else as a final safeguard or hedge against risk. Martin [13] considers surveying costs in a Bayesian context in order to determine more accurately the transition probabilities. An area of future research would be to combine our approach with his in order to estimate the tradeoffs of increased value by not surveying but decreased certainty about the estimates of the transition probabilities.

Policy improvement stage

$$\hat{\delta}(i, s) = \underset{a}{\operatorname{argmax}} [\pi(s, i) \gamma(a) + \beta \pi(s, i) P(a) f(0)]$$

$$\hat{\delta}(i, s') = \underset{a}{\operatorname{argmax}} [\pi(s, i) \gamma(a) + \beta \max_{\ell} \pi(s, i) P(a) \hat{\alpha}(\ell, s' + 1)]$$

$$1 \leq s' \leq s - 1$$

where $\hat{\alpha}(i, s) = \gamma(\hat{\delta}(s)) + \beta P(\hat{\delta}(s)) f(0)$

$$\hat{\alpha}(i, s') = \gamma(\hat{\delta}(s')) + \beta P(\hat{\delta}(s')) \hat{\alpha}(\ell, s' + 1)$$

If policy $\hat{\delta} = \delta$, then $\delta = \delta^*$

Set $\delta = \hat{\delta}$

Policy evaluation

For policy δ , calculate $f(i, s')$, $0 \leq s' \leq s$ from the following equations:

$$f(i, s', \pi(s', i)) = \pi(s', i) \gamma(\delta(i, s')) + \beta f(i, s' + 1, \pi(s' + 1, i))$$

$$f(i, s) = \pi(s, i) f(0) - C(s)$$

where $\pi(i, 0) = e_i$; $\pi(s', i) = \pi(s' - 1, i) P(\delta(i, s' - 1))$

Calculate $\alpha(i, s')$ from the following equations

$$\alpha(i, s') = \gamma(\delta(i, s')) + \beta P(\delta(i, s')) \alpha(i, s' + 1) \quad 0 \leq s' \leq s - 1$$

$$\alpha(i, s) = f(0) - C(s) \underline{\underline{1}}$$

Figure 1. Policy iteration for fixed s .

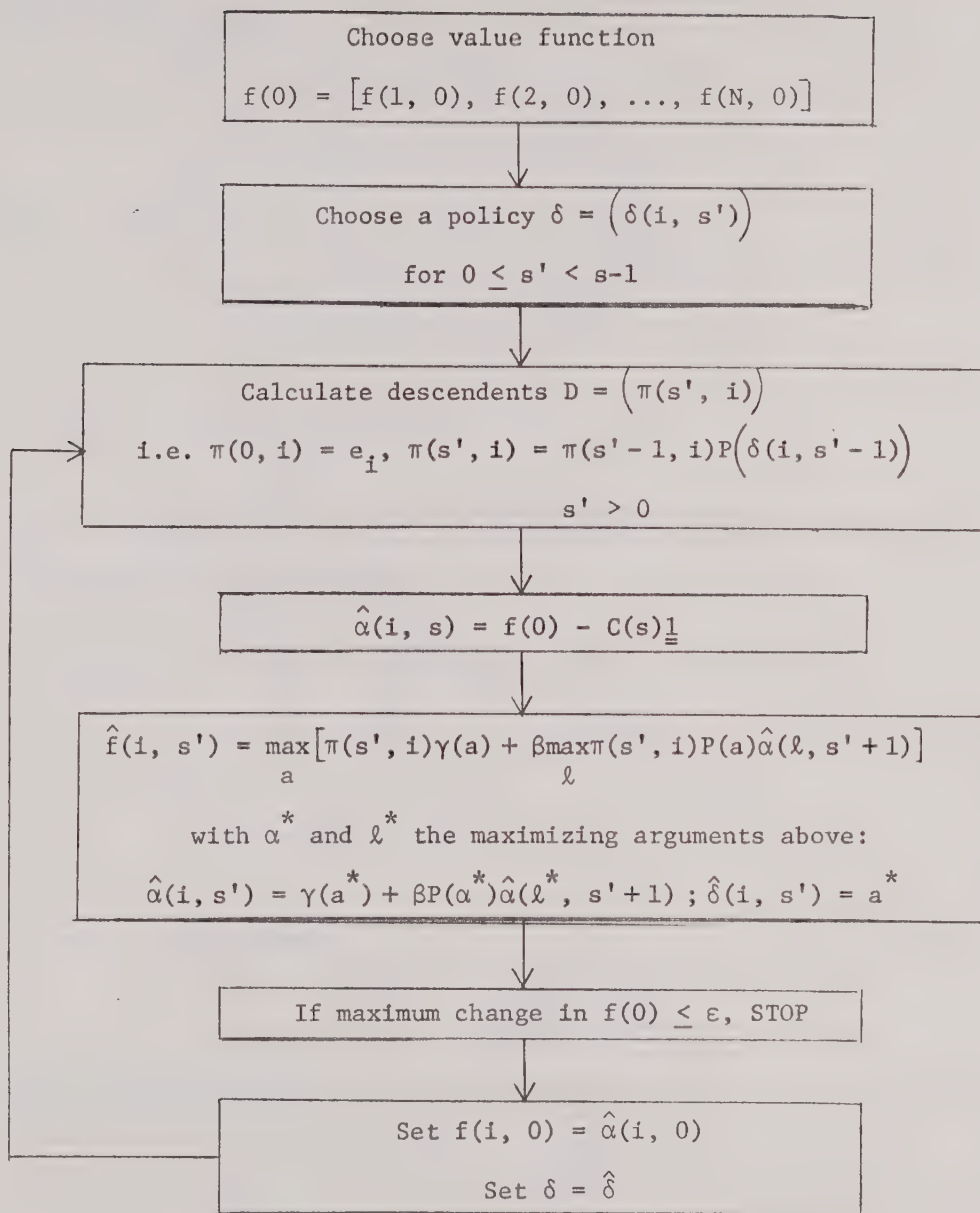


Figure 2. Value iteration algorithm for fixed s .

Policy evaluation

For policy δ , calculate $f(i, s')$, $0 \leq s' \leq s$ from the equations:

$$f(i, 0) = \pi(0, i) \gamma(\delta(i, 0)) + \beta f(i, 1)$$

for $1 \leq s' \leq s-1$:

$$f(i, s', \pi(s', i)) = \begin{cases} \pi(s', i) \gamma(\delta(i, s')) + \beta f(i, s'+1, \pi(s'+1, i)) & \text{if } \delta(i, s') \neq A+1 \\ \pi(s', i) f(0) - C(s) & \text{if } \delta(i, s') = A+1 \end{cases}$$

$$f(i, s, \pi(s, i)) = \pi(s, i) f(0) - C(s) \underline{1}$$

where $\pi(0, i) = e_i$, $\pi(s', i) = \pi(s'-1, i) P(\hat{\delta}(i, s'-1))$, $s' \geq 1$

calculate the $\alpha(i, s')$ from:

$$\alpha(i, 0) = \gamma(\delta(i, 0)) + \beta P(\delta(i, 0)) \alpha(i, 1)$$

$$\alpha(i, s') = \begin{cases} \gamma(\delta(i, s')) + \beta P(\delta(i, s')) \alpha(i, s'+1) & \text{if } \delta(i, s') \neq A+1 \\ f(0) - C(s) \underline{1} & \text{if } \delta(i, s') = A+1 \end{cases}$$

$$\alpha(i, s) = f(0) - C(s) \underline{1}$$

Set $\delta = \hat{\delta}$

Policy improvement

$$\hat{\delta}(i, s') = \underset{a, A+1}{\operatorname{argmax}} \begin{cases} \pi(s, i) \gamma(a) + \beta \max_{\ell} \pi(s, i) P(a) \hat{\alpha}(\ell, s'+1) \\ \pi(s, i) f(0) - c(s) \end{cases}$$

$$\text{where } \hat{\alpha}(i, s') = \begin{cases} \gamma(\hat{\delta}(s')) + \beta P(\hat{\delta}(s')) \hat{\alpha}(\hat{\ell}, s'+1) \\ f(0) - c(s) \end{cases}$$

If $\hat{\delta} = \delta$, then $\delta = \delta^*$

Figure 3. Policy iteration for variable survey interval.

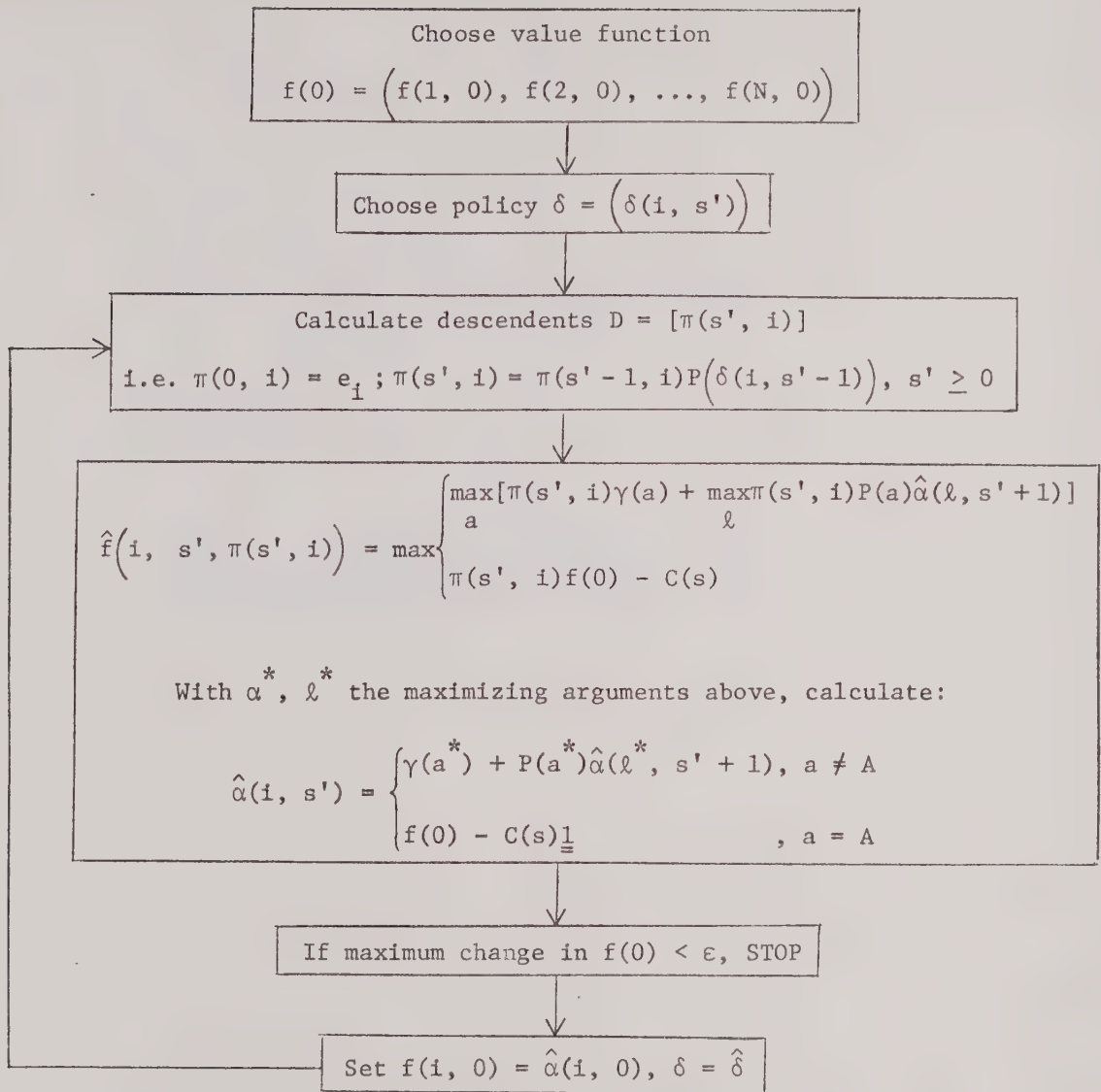


Figure 4. Value iteration for variable survey interval.

SEAMOUNT FISHERY, FOREIGN VESSEL OBSERVER REPORT

ASO MARU (May 27-July 10, 1979)

By

George C. Evering, Jr.
Southwest Fisheries Center Honolulu Laboratory
National Marine Fisheries Service, NOAA
Honolulu, HI 96812

July 1979

August 20, 1979

TO: Office of International Fisheries Affairs, F4, NMFS, NOAA, Wash. D.C.

FROM: Richard S. Shomura, Director, Honolulu Laboratory

SUBJECT: Correction to SWFC Admin. Rep. H-79-14

Please make the following correction to SWFC Admin. Rep. H-79-14, Seamount fishery, foreign vessel observer report, Aso Maru (May 27-July 10, 1979), July 1979:

Page 4, paragraph 1a, subheading "Fat type," line 5, "Average weight,"

1.53 kg should be corrected to 0.53 kg.

VLI:vli (for G. Evering)

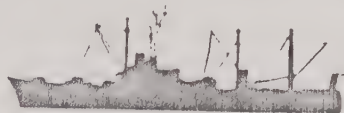
bc: Evering
HL

cc: Administrator, WPP0, FSW1
SWFC, SWEC F14
SWR, FSW

The Aso Maru was designated to the Mid-Pacific Seamount Fishery by the Nippon Suisan Company from May to September 1979. There were nine eligible seamounts suitable for trawling.

Vessel Statistics

Permit number:	JA-78-0388A
Length:	95.11 m
Gross tonnage:	3,608.29
Engine type:	Diesel
Hull number:	100883
Year commissioned:	1964
Owner:	Nippon Suisan Kaisha
Home port:	Tobata, Japan
Vessel type:	Freezer-factory. Independent stern trawler
Net tonnage:	1,968.81
Width	16 m
Draft:	6.6 m
Horsepower:	3,900
Registration number:	TOEN-701
Radio call sign:	JMVD



Personnel

Captain:	Mr. Tamura
Number of officers:	9
Number of crew:	35
Galley and steward:	8
Deck:	27
Processing:	18
Total ship complement:	55
Experience in seamount fishery:	
Captain	5 seasons
Chief Officer	2 seasons
2d Officer	1 season

Trawl Gear

See attachment 1 for dimensions. The net was modified by replacing three of the six center bobbins with larger cylindrical bobbins composed of hard rubber or fiber, and by extending the ground gear along the tow leg by adding bobbins. Both alterations supposedly reduce "hangups."

Area of Operation

<u>Seamounts</u>	<u>Latitude</u>	<u>Longitude</u>
Kinmei	35°00'N	171°45'E
Milwaukee seamount group:		
Yuryaku	32°40'N	172°15'E
Kanmu	32°10'N	173°00'E
Colahan	31°15'N	176°00'E
Fishery conservation zone:		
Northwest Hancock	30°15'-16'N	178°42'-44'E
Southeast Hancock	29°43'-49'N	179°02'-06'E
K Bank	29°40'N	179°20'E

TRAWL RESULTS

Target Species

Common names:	Armorhead, boarfish, tsubodai
Scientific name:	<u>Pentaceros richardsoni</u>
Species code:	080
Common names:	Alfonsin, kinmedai
Scientific name:	<u>Beryx splendens</u>
Species code:	081

The trawl set was always commenced before contact with the seamount. Trawling was on or just a few meters above the bottom. However, the net was not hauled inboard and the cod end inspected after each pass. It was considered lost fishing time to bring in a nearly empty cod end when the fish-finders indicated little in the way of commercial concentrations. Usually only the doors were brought to the gallows for the turn, and after the turn the warp paid out again immediately. The catch would probably be well less than 1 metric ton (MT). Thus, using the duration of the haul to compute catch per unit effort (CPUE) could prove to give erroneous results for either of two reasons: (1) One haul comprises several passes and includes the time of bringing the doors to the gallows and completing a 180° turn and (2) the catch could not be estimated per pass because the cod end could not be inspected.

The net was fished (kept in the water; not bottom time) for an average of 18.6 min per haul on K Bank. Hauls on southeast Hancock averaged 134.3 min and on northwest Hancock 98.2 min.

Outside the fishery conservation zone on D Bank (30°22'N, 177°35'E) the trawl was towed 10.7 min per haul. On Colahan the average was 94.4 min per haul. On the Milwaukee Seamounts F(A) Bank (southern Hanmu) hauls averaged 83.4 min, F(B) (northern Kanmu) 61.3 min per haul, and F(C) (Yuryaku) 70 min per haul. Kinmei had an average haul of 75.7 min.

Of a total of 561.7 MT caught between May 29 and July 10, 1979, 177.0 MT or 32% were composed of armorhead. Alfonsin totaled 304.2 MT or 54% of the catch. Other species comprised 80.4 MT or 14% of the total. Thirty-seven percent of the catch was taken within the fishery conservation zone. Fifty-six percent or 24 days of the total fishing days of my stay were spent within the fishery conservation zone.

The largest single catch within the fishery conservation zone was 8.2 MT. Of 138 hauls in the fishery conservation zone, 41 produced catches greater than or equal to 2 MT. There were 12 zero catch hauls.

In the fishery conservation zone 96% of the armorhead and 91% of the alfonsin were caught between 1800 and 0600. The first 12 days of fishing produced 90.2 MT or 66% of the total armorhead. This period also yielded 9.1 MT of alfonsin or 37%. After an 18-day cooling off period the other 34% of armorhead and 63% of alfonsin were taken in 12 days.

The largest catch outside the fishery conservation zone was 21 MT of almost exclusively juvenile alfonsin. There were 29 zero catch hauls outside and 40 hauls were greater than 2 MT. A total of 140 hauls were made.

Of the 41 total zero catch hauls at least 25 are known positively to have been caused by a net hangup, terminating the haul.

SAMPLING RESULTS

1. Armorhead

There are two distinct types of armorheads, fat and lean. These may have an ecological import and are therefore recorded separately.

a. Hancock Seamounts

The catch composition average was 95% for lean (100 fat types and 1,913 lean types).

Lean type

Number measured, sexed, and weighed: 1,001
 Sex ratio: Male 443 (44%)
 Female 558 (56%)
 Average length: 294 mm Range: 253-340 mm
 Average weight: 0.31 kg

Fat type

Number measured, sexed, and weighed: 43
 Sex ratio: Male 21 (48%)
 Female 22 (52%)
 Average length: 310 mm Range: 270-329 mm
 Average weight: 0.53 kg

b. K Bank

Lean type

Number measured, sexed, and weighed: 25
 Sex ratio: Male 11 (44%)
 Female 14 (56%)
 Average length: 293 mm Range: 276-308 mm
 Average weight: 0.39 kg

Fat type

Number measured, sexed, and weighed: 10
 Sex ratio: Male 8
 Female 2
 Average length: 290 mm Range: 263-314 mm
 Average weight: 0.53 kg

2. Alfonsin (Beryx splendens)

Alfonsin made up an important part of the total catch this season. However, 92% of the total weight was taken outside the fishery

conservation zone. The other species of alfonsin, Beryx decadactylus, made up well less than 1% of the total catch of alfonsin outside the fishery conservation zone. Outside the fishery conservation zone the Aso Maru was selectively fishing for schools of juvenile alfonsin during the dark hours. A very rough estimate would be that 20% of the alfonsin harvested was sent to the meal factory due to the great damage sustained to them by the long hauls.

a. Hancock Seamounts

Number measured, sexed, and weighed: 645
 Sex ratio: Male 344 (54%)
 Female 301 (46%)
 Average length: 234 mm Range: 143-401 mm

The range of weight is too wide (<0.1->1 kg) and the individual weight too variable to yield a reliable figure by averaging. However, the average weight of juvenile alfonsin < 200 mm is 0.13 kg.

b. K Bank

Number measured, sexed, and weighed: 39
 Sex ratio: Male 16 (41%)
 Female 23 (59%)
 Average length: 208 mm Range: 198-356 mm

3. Other commercial species

Outside the fishery conservation zone were commercial concentrations of Helicolenus avius, Epigonus atherinoides, Zenopsis nebulosa, Erythocles schlegelii, and Ariomma lurida. Within the fishery conservation zone only E. schlegelii was harvested in large enough quantities to be considered more than an incidental species.

4. Coral

Approximately 37 kg of black coral, Antipathes species, was uprooted outside the fishery conservation zone. Only 1 kg was from within the zone.

SHIPBOARD PRODUCTS (Hancock Seamounts and K Bank)

1. Armorhead

Armorhead were frozen after machine heading and gutting. The recovery ratio is estimated to be about 50% of the total weight. Only the head and viscera were designated as meal--never flesh.

2. Alfonsin

A considerable amount of alfonsin less than 200 mm were sent to the meal factory because the duration of the tow damaged the fish badly. The larger fish were usually machine headed and gutted; recovery ratio was 40%.

3. Other species

Zenopsis nebulosa, Ocycirus japonicus, Promethichthys prometheus, Priacanthus boops, squalids, and carcharhinids were filleted with core and frozen. Erythocles schlegelii, Helicolenus avius, and Epigonus atherinoides were frozen whole. Large Sebastes species and serranids were headed, gutted, and frozen.

4. Other products

The daily reduction could not be figured because of "carryover" in raw product from the previous day. Raw product reduction was approximately 225 MT (whole fish, viscera, and heads) which yielded about 45 MT of meal and 20 kl of oil.

ITINERARY

May 26, 1979	- 1050, departed Honolulu, Hawaii
	- 1415, arrived Midway
May 27, 1979	- Embarked <u>Aso Maru</u>
May 29, 1979	- Began sampling
July 10, 1979	- Sampling ended
	- 1000, debarked <u>Aso Maru</u>
	- 1500, arrived Honolulu.

RECORDS

A daily Scientists Log, Daily Trawl Haul Form, Size-Frequency Log, and Species Composition From Basket Samples records were kept.

PERSONNEL

George C. Evering, Jr., Observer, National Marine Fisheries Service,
Southwest Fisheries Center, Honolulu Laboratory

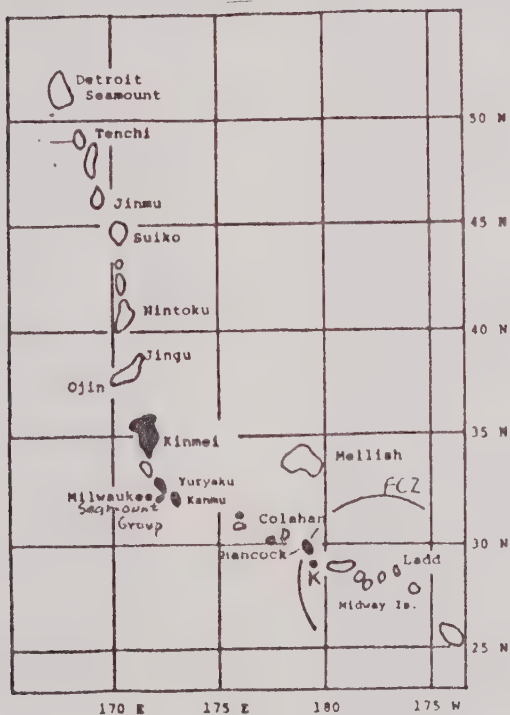


Figure 1.--Important seamounts in North Pacific Ocean.

Table 1.--Trawl catch by species and area (in metric tons).

<u>Species</u>	<u>Fishery conservation zone</u>	<u>Outside</u>
Armorhead	135.5	41.5
Alfonsin	24.7	279.5
Others (listed below)	45.2	33.2
<u>Erythrocles schlegelii</u>		<u>Benthodesmus tenuis</u>
<u>Antigonia eos</u>		<u>Brotulidae sp.</u>
<u>Chloropthalmus oblongus</u>		<u>Notacanthus seppinis</u>
<u>Arionma lurida</u>		<u>Peristedion engyceros</u>
<u>Macroramphosus gracilus</u>		<u>Brembradium roseum</u>
<u>Polymixia japonica</u>		<u>Coelorynchus gladius</u>
<u>Priacanthus boops</u>		<u>Alopias superciliosus</u>
<u>Grammatonotus laysanus</u>		<u>Eumegistus illustris</u>
<u>Decapterus russelli</u>		<u>Sebastes spp.</u>
<u>Collybus drachme</u>		<u>Draconetta hawaiiensis</u>
<u>Scomber japonicus</u>		<u>Alopias pelagicus</u>
<u>Chascanopsetta prorigera</u>		<u>Hoplichthys platophrys</u>
<u>Parabothus coarctatus</u>		<u>Sternoptyx diaphana</u>
<u>Promethichthys prometheus</u>		<u>Ectreposebastes imus</u>
<u>Ruvettus pretiosus</u>		<u>Chauliodus sloani</u>
<u>Etmopterus villosus</u>		<u>Serranidae sp.</u>
<u>Squalus fernandinus</u>		<u>Parapercis schauinslandi</u>
<u>Squalus blainevillei</u>		<u>Aphareus rutilans</u>
<u>Lotella maximowiczi</u>		<u>Decapterus pinnulatus</u>
<u>Zenopsis nebulosa</u>		<u>Diaphos adenomus</u>
<u>Laemonema rhodochir</u>		<u>Physiculus grinelli</u>
<u>Epigonus atherinoides</u>		<u>Pseudanthias kellogi</u>
<u>Argentinidae sp.</u>		<u>Carcharhinus obscurus</u>
<u>Beryx decadactylus</u>		<u>Carcharhinus amblyrynchus</u>
<u>Helicolenus avius</u>		<u>Ariosoma bowersi</u>
<u>Microstomus sp.</u>		<u>Gonostomatidae spp.</u>
<u>Callionymidae sp.</u>		<u>Carcharhinus falciformis</u>
<u>Rynchocymba nystromi</u>		<u>Congridae spp.</u>
<u>Hydrolagus colliei</u>		<u>Carcharhinidae spp.</u>
<u>Myctophidae sp.</u>		<u>Carcharhinus galapagensis</u>
<u>Echinorhinus cookei</u>		<u>Urotrygon daviesi</u>
<u>Dalatias licha</u>		<u>Dasyatis latus</u>
<u>Etmopterus lucifer</u>		<u>Naucrates ductor</u>
<u>Isurus paucus</u>		<u>Etelis carbunculus</u>
<u>Isurus oxyrinchus</u>		<u>Odontaspis ferox</u>
<u>Alopias vulpinus</u>		<u>Trachurops crumenophthalmus</u>
<u>Pseudotriakis acrages</u>		<u>Antennariidae spp.</u>
<u>Lophiomus miacanthus</u>		
<u>Ocyrops japonicus</u>		
<u>Synodontid sp.</u>		

Note: Checklist incomplete pending further species identification.

Table 2.--Catch-per-unit-effort by species and area.

Area	No. hauls	Total minutes (trawl in water)	Armorhead		Alfonsin		Others		All species	
			Total catch (kg)	Kg/min	Total catch (kg)	Kg/min	Total catch (kg)	Kg/min	Total catch (kg)	Kg/min
K Bank	12	223	927	4.16	6,816	30.56	274	1.23	8,017	35.95
Southeast Hancock	69	9,570	66,953	6.99	10,712	1.12	2,120	0.22	98,866	10.33
Northwest Hancock	57	5,595	67,632	12.08	7,198	1.29	23,690	4.23	98,520	17.59
D Bank	15	160	3,218	20.11	5,204	32.53	664	4.15	9,086	56.79
Colahan	31	2,925	27,667	9.46	38,548	13.18	6,456	2.21	72,671	24.84
Kanmu F(A)	16	1,335	3,088	2.31	76,420	57.24	6,962	5.21	86,470	64.77
Kanmu F(B)	32	1,960	5,898	3.01	70,984	36.22	4,866	2.48	81,748	41.71
Yuryaku F(C)	18	1,260	960	0.76	73,253	58.14	980	0.78	75,193	59.68
Kinmei	28	2,120	695	0.33	15,097	7.12	13,330	6.29	29,122	13.74

ASO-MARU

Attachment #1 NET DIMENSIONS AND CHARACTERISTICS

Type of Vessel STERN TRAWLER

Observation Period 05/27/79-7/10/79

Trawl Doors: Shape Square

Type Vertical Steel

Dimensions 2.2 m. x 4.4 m.

Weight 3000 kg.

Dandyline Length 120 m.

Floats: Number 46

Size 360 mm

Material Styrofoam

Shape Ball

Bobbins: Number 34 Bobbins

Size 530 mm x 500 mm

Material Iron & Rubber

Shape Ball & cylinder



Headrope Length 50.8 m.

Footrope Length 59.0 m.

Vertical Opening 7.8 m.

Horizontal Opening 20 m.

Warp Length 2200 m.

Wing Mesh Size 180 mm.

Square Mesh Size 150 mm.

Belly Mesh
Size 90 mm.

Net Recorder:

Name FURUNO

Model Number FNR 50

Frequency 50 KHz

Fish Finder:

Name SANKEN-WIDE 320

Model Number WSV2-16 NO 50070

Frequency 172 KHz / 50.4 KHz

Paper Type - Wet X Dry

Speed of Advance 1.5 cm / minute



U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
NATIONAL MARINE FISHERIES SERVICE
Southwest Fisheries Center
Honolulu Laboratory
P. O. Box 3830
Honolulu, Hawaii 96812

August 20, 1979

F142:VLI

TO: Office of International Fisheries Affairs, F4, NMFS, NOAA, Wash. D.C.

FROM: Richard S. Shomura, Director, Honolulu Laboratory

SUBJECT: Correction to SWFC Admin. Rep. H-79-14

Please make the following correction to SWFC Admin. Rep. H-79-14, Seamount fishery, foreign vessel observer report, Aso Maru (May 27-July 10, 1979), July 1979:

Page 4, paragraph 1a, subheading "Fat type," line 5, "Average weight,"

1.53 kg should be corrected to 0.53 kg.

cc: Administrator, WPPO, FSW1
SWFC, F14
SWR, FSW



U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
NATIONAL MARINE FISHERIES SERVICE
Southwest Fisheries Center
Honolulu Laboratory
P. O. Box 3830
Honolulu, Hawaii 96812

August 8, 1979

Fl42:RFS

TO : Administrator, WPPO - FSW1
FROM : *Richard S. Shomura*
Richard S. Shomura, Director, Honolulu Laboratory
SUBJECT : Foreign Observer Report

Attached is a copy of George Evering's trip report
entitled "Seamount Fishery, Foreign Vessel Observer Report,
Aso Maru (May 27-July 10, 1979)."

Attachment

Fl4, NMFS, Wash. -



U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
NATIONAL MARINE FISHERIES SERVICE
Southwest Fisheries Center
Honolulu Laboratory
P. O. Box 3830
Honolulu, Hawaii 96812

August 8, 1979

Fl42:RFS

TO : Director, Office of Intl. Fisheries Affairs, NMFS - Fl4
FROM : *Richard S. Shomura*
Richard S. Shomura, Director, Honolulu Laboratory
SUBJECT : Foreign Observer Report

Attached is a copy of George Evering's trip report
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Aso Maru (May 27-July 10, 1979)."

Attachment



U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
NATIONAL MARINE FISHERIES SERVICE
Southwest Fisheries Center
Honolulu Laboratory
P. O. Box 3830
Honolulu, Hawaii 96812

August 8, 1979

F142:RFS

TO : Center Director, SWFC, La Jolla - F14
FROM : *Richard S. Shomura*
Richard S. Shomura, Director, Honolulu Laboratory
SUBJECT : Foreign Observer Report

Attached is a copy of George Evering's trip report
entitled "Seamount Fishery, Foreign Vessel Observer Report,
Aso Maru (May 27-July 10, 1979)."

Attachment



U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
NATIONAL MARINE FISHERIES SERVICE
Southwest Fisheries Center
Honolulu Laboratory
P. O. Box 3830
Honolulu, Hawaii 96812

August 8, 1979

F142:RFS

TO : Regional Director, Southwest Region, Terminal Island - FSW
FROM : *Richard S. Shomura*
Richard S. Shomura, Director, Honolulu Laboratory
SUBJECT : Foreign Observer Report

Attached is a copy of George Evering's trip report
entitled "Seamount Fishery, Foreign Vessel Observer Report,
Aso Maru (May 27-July 10, 1979)."

Attachment

August 7, 1979

F142

Mr. Susumu Kato, Tiburon Laboratory

Irene H. Toyomura, Honolulu Laboratory

SWFC Admin, Rep. H-79-14

Director Shomura asked that I send you a copy of the Aso Maru trip report prepared by George Evering, our foreign observer on that cruise. We hope you find this report useful on your forthcoming trip to Japan.

Enclosure

11-79-~~11~~ 15

A SYSTEMATIC APPROACH TO DETERMINING MEAN-VARIANCE TRADE OFFS
WHEN MANAGING RANDOMLY VARYING POPULATIONS

Roy Mendelsohn
Southwest Fisheries Center
National Marine Fisheries Service, NOAA
Honolulu, Hawaii 96812

1. INTRODUCTION

In several recent papers, Beddington and May [1] and May et al. [5] have raised the issue of high variances in the equilibrium harvests when stochastic populations are harvested at high levels. Their concerns suggest that there may be desirable trade offs between the average per period harvest and the long-run (ergodic) variance of the harvests. In order to determine this trade off in a practical manner, what is needed is a systematic method to determine the mean-variance trade off among some subset of policies with desirable properties.

In this paper, such a methodology is suggested. New results by Henig [3] and White and Kim [11] on multiobjective Markov decision problems are combined with an approach to "smooth out" year-to-year fluctuations in the harvest size, an approach studied analytically in Mendelssohn [6]. This leads to a systematic trade off of the mean and variance for only a subset of policies that are Pareto optimal policies for two well defined objectives. The algorithm is applied to a model suggested by Mathews [4] for salmon runs off Bristol Bay, Alaska. Section 2 describes the model and the objective functions to be considered. Section 3 discusses the solution procedure and computational considerations. Section 4 shows the results of the analysis when applied to the example.

2. THE MODEL

A population is to be managed over an infinite planning horizon. At the start of each period t , an initial population size x_t is observed. During period t an amount z_t is harvested, leaving a population size of $y_t = x_t - z_t$ at the end of the period. The population size x_{t+1} at the start of the next period is a random function of y_t and of a random variable D_t , that is:

$$x_{t+1} = s[y_t, D_t] \quad (2.1)$$

where the random variables $D_1, D_2, D_3, \dots$ are assumed to be independent and identically distributed as the generic random variable D . If a population size x is observed and a decision y is made, an expected one-period return of $g(x, y)$ is received. The returns are discounted by a factor α , $0 \leq \alpha < 1$, and letting E be the expectation operator, it is desired to:

$$\begin{aligned} &\text{maximize } E \sum_{t=1}^{\infty} \alpha^{t-1} g(x_t, y_t) \\ &\text{s.t. (2.1); } y_t \in Y(x_t) \end{aligned} \quad (2.2)$$

where $Y(x)$ constrains the population size y that can be left given x . For $\alpha = 1$, the summation in (2.2) will not converge. The results presented can be used in this instance by allowing α to approach 1 from below. A simple example of (2.2) is to maximize total expected discounted yield, that is

$$\begin{aligned} &\text{maximize } E \sum_{t=1}^{\infty} \alpha^{t-1} (x_t - y_t) \\ &\text{s.t. (2.1); } 0 \leq y_t \leq x_t \end{aligned} \quad (2.3)$$

A policy that maximizes (2.2) or (2.3) may produce harvest sizes that fluctuate sharply from period to period. This may not be undesirable. However, it is natural to desire to obtain a feel of what is lost if these fluctuations are smoothed out. One method [6] to "smooth out" the period-to-period fluctuations in harvest size is to assess a cost for any change between z_{t-1} and z_t . Specifically, suppose for any decrease in the harvest size a cost of $\lambda \cdot (z_{t-1} - z_t)$ is assessed, and for any increase in the harvest size a cost of $\epsilon \cdot (z_t - z_{t-1})$ is assessed. Letting $e = \frac{\lambda - \epsilon}{2}$ and $c = \frac{\lambda + \epsilon}{2}$, this cost can be compactly represented as $e \cdot (z_{t-1} - z_t) + c \cdot |z_t - z_{t-1}|$. In [6, 7] the approach is to combine the two objective functions. That is, the new optimization problem becomes:

$$\begin{aligned} \text{maximize } E \sum_{t=1}^{\infty} \alpha^{t-1} & \left(g(x_t, y_t) - e(z_{t-1} - (x_t - y_t)) - c \cdot |(x_t - y_t) - z_{t-1}| \right) \\ \text{s.t. (2.1); } & y_t \in Y(x_t); z_t = x_t - y_t \end{aligned} \quad (2.4)$$

To smooth the total fluctuations, it is natural to assume $\lambda = \epsilon$. This implies $e = 0$ and $c = \lambda = \epsilon$, so that the one-period return for any state (x, z) is:

$$g(x, y) - \lambda \cdot |x - y - z| \quad (2.5)$$

The desired trade off could be approximated by varying λ , and solving (2.4) for each value of λ , and then calculating the ergodic distribution of each policy found. However, there is a more systematic method to achieve the same ends. Assume each period there are two

separate returns, $g(x, y)$ and $-\lambda \cdot |x - y - z|$. Then it is desired to find the set of Pareto optimal values and associated policies.

For any policy $\delta(x)$ defined for all x in some set of possible states X , let $v_\delta = \{v_\delta^i\}$ be the vector value of expected returns when following policy δ , that is it is a two-dimensional vector where v_δ^i is the expected return for objective i , $i = 1, 2$, when following policy δ . Let V be the set of all possible return vectors. Then v_{δ^*} is Pareto optimal and δ^* is a Pareto optimal policy if there exists no other $v_\delta \in V$ such that:

$$\begin{aligned} v_\delta^i &\geq v_{\delta^*}^i && \text{for } i, j = 1, 2 \\ v_\delta^j &> v_{\delta^*}^j && \text{for some } j \end{aligned} \tag{2.6}$$

Intuitively, (2.6) says that a policy δ^* is a Pareto optimal policy if any other policy δ that increases the expected return for one objective decreases the expected return for the other objective. Thus when determining the mean-variance trade off, policies are included if they lower the costs due to fluctuations as they lower the "true" value of the harvest, or vice versa, increase the "true" value of the harvest if they increase the assessed cost due to fluctuations in harvest size.

Given the set of Pareto optimal policies, the ergodic distribution for each policy is calculated. The mean and variance are then readily calculated from the ergodic distributions.

3. COMPUTATIONAL TECHNIQUES AND CONSIDERATIONS

In this section an approach to finding the set of Pareto optimal policies is described. Henig [3] has provided the theoretical foundation

and White and Kim [11] an algorithm for efficiently calculating the Pareto optimal set. Suppose the problem has been redefined on a discrete grid. Let $p(i, j, a_i)$ be the probability of going to state j from state i when the action chosen is a_i . Here a state i refers to a particular vector pair (x, z) , that is the present population size and the harvest size last period. Let $P[\delta]$ be the transition matrix for policy δ and let $P_{(x, z)}[\delta]$ be the row of $P[\delta]$ for state (x, z) . Let $r[(x, z), \delta]$ be the two-dimensional row vector of rewards when (x, z) is the state and δ is the policy, that is $r^i[(x, z), \delta]$ is the immediate reward for objective i when (x, z) is the state and policy δ is being followed. Let γ be a two-dimensional vector such that $0 \leq \gamma^i \leq 1$ and $\sum_i \gamma^i = 1$. Let f be any real-valued two-dimensional vector, and define the following operators:

$$[L_\delta f](x, z) = r[(x, z), \delta]\gamma + \alpha P_{(x, z)}[\delta]f \quad (3.1a)$$

$$\text{and} \quad [Uf](x, z) = \max_{\delta} [L_\delta f](x, z) \quad (3.1b)$$

Let $\bar{f}$ be the unique vector where equality is obtained in (3.1b), and let δ^* be a maximizing policy. Then Henig [3, p. 60-61] proves that δ^* is a Pareto optimal policy if and only if it is a policy where the maximum is obtained in (3.1b) for some value of γ . Writing out (3.1) specifically in our context, a policy is Pareto optimal if and only if it achieves, for some γ , the maximum of:

$$\begin{aligned} \bar{f}(x, z) = \max_{y \in Y(x)} \{ & \gamma g(x, y) - (1 - \gamma)\lambda \cdot |x - y - z| \\ & + \alpha \bar{f}(s[y, D], x - y) \}. \end{aligned} \quad (3.2)$$

White and Kim [11] show that by including γ in the state vector, (3.2) can be treated as a partially observed Markov decision process, and use the special structure inherent in this problem to derive an efficient version of Sondik's [10] algorithm for partially observed MDPs.

The algorithm in White and Kim [11] solves a discrete state and action version of (3.2) simultaneously for all values of γ in the interval $[0, 1]$. This readily can be seen to be the equivalent of letting λ vary in (2.5). Therefore, without loss of generality, λ can be set equal to one (which can also be seen by rescaling the return function g at the outset).

Given the set of Pareto optimal policies, which must be finite in number, the ergodic probability distribution, assuming an irreducible transition matrix, can be calculated readily. Let π_0 be an initial guess at this distribution, and calculate successively for a given δ^* :

$$\pi_n = \pi_{n-1}^T P[\delta^*] \quad (3.3)$$

where T denotes the vector transpose. The iterations stop when the maximum difference between π_n and π_{n-1} is at a satisfactory level.

While the iterations described in (3.3) are straightforward, they are inefficient and impractical. Suppose the population size is defined on a 25-point grid. Then there are 25 possible harvest sizes, so that there are 625 states. This implies for any policy δ^* that $P[\delta^*]$ has 390,625 entries, which would require roughly 1,562K of computer storage. However, $P[\delta^*]$ is sparse since if $x - \delta^*(x, z) = z'$, then a transition only can be made to states (x, z') next period. Permute row and columns of $P[\delta^*]$ so that the columns run through all values of x for each fixed value of

z, and order the rows so that all states that harvest the same amount when following δ^* are together. This yields a blocked matrix as in Table 1. A solution procedure is to iteratively solve (3.3) for each block in order until convergence is reached. This is precisely block Jacobi iterates as described in Young [12]. The advantage is both a reduction in computer storage, since only the smaller blocks are used one at a time, and also an acceleration of convergence [12, chapter 14].

4. EXAMPLE

Mathews [4] has suggested the following model for salmon runs on the Wood River off Bristol Bay, Alaska. Let x_t be the number of recruits at the start of period t , and y_t the number of spawners at the end of period t . Then:

$$x_{t+1} = \exp\{D_t\} 4.077 y_t \exp\{-0.800 y_t\} \quad (4.1)$$

$$D \sim \text{Normal}(0, 0.2098)$$

The example problem is defined on a grid of 15 equally spaced points on $(0, 5]$ in units of 10^6 fish. The procedure used is described in detail in [7]. The constraint set $Y(x)$ is assumed to be $Y(x) = \{y : 0 \leq y \leq x\}$, α is arbitrarily set at 0.97, and the primary one-period return is simply yield, $x_t - y_t$, while the second objective is $-\lambda \cdot |x_t - y_t - z_{t-1}|$ with $\lambda = 1$. In applications, it will be necessary to vary α to test the sensitivity of the results to the change in the discount factor.

The mean-standard deviation trade off curve using the techniques of section 3 is shown in Figure 1. The points where $\gamma = 0.0, 0.25, 0.5, 0.75, 1.0$ are identified in order to show how the trade off varies with γ . It is clear from Figure 1 that substantial reductions can be

Fig. 1

made in the standard deviation with only minimal reductions in the mean per period harvest. At $\gamma = 0.75$ as compared with $\gamma = 1$, the mean per period harvest has only been reduced from 1.26×10^6 to 1.2×10^6 fish (a reduction of 4.76%), while the standard deviation has been reduced from 0.83×10^6 to 0.70×10^6 fish, a reduction of 15.66%.

Fig. 2 Figure 2 shows the change in the ergodic distribution for selected values of γ . As γ decreases, the tails become shorter, the mode higher and lower. The distribution is bimodal in the approximate range 0.8-0.6, and becomes extremely steep and narrow as γ nears zero.

Fig. 3 Figures 3(a)-(e) show an optimal policy for these same values of γ . The figures are read by finding the appropriate (x, z) point on the figure, following the arrow in that region, and the resulting z value is an optimal harvest for that state. Region I is the region in which the harvest size decreases, in region II the harvest size remains the same, and in region III the harvest size increases. Figures 2 and 3 show that as γ varies from 1.0 to 0.0, region II increases at the expense of region III, until region III disappears entirely, and while region I does not change in size, the probability of ever being in that region decreases to zero.

DISCUSSION AND SUMMARY

New results on multiobjective Markov decision problems have been combined with an approach to smoothing harvests to produce a technique for determining the mean-variance trade off among the "best" subset of harvesting policies. The technique has been found to be computationally reasonable, and produces the maximum amount of information for the decisionmaker.

The suggested technique greatly extends the analysis in Beddington and May [1] and May et al. [5]. While the particular example used to illustrate the algorithm has Gaussian noise, the general formulation is not restricted to this class of models as in the cited references. Moreover, in these references, they set the growth term equal to zero, and assume that the one-period distribution of returns from any policy is equivalent to the long-run distribution of returns when following the same policy (i.e., they examine behavior when $dx/dt = 0$). This assumption is very often false. The proposed optimization methods calculate explicitly the long-run distribution that arises when following a given policy. Also, by restricting the decision set $Y(x)$, the proposed models include as a subset models that require fixed effort or fixed harvests. However, since $Y(x)$ need not be so restricted, the class of decision processes that can be considered is much richer.

Moreover, fixed effort or fixed harvest policies arise from conclusions based on deterministic models of population dynamics, conclusions that may not be appropriate for randomly varying populations. (In practice, most fisheries management, for example, varies the estimate of maximum sustained yield each year as the population changes.) By not being restricted to fixed effort or fixed harvest policies, it is possible to determine what the loss in value is from using such policies. The example in section 4 suggests that the best fixed harvest policy reduces significantly the average per period harvest. It is proven analytically in [2, 8, 9] that optimal harvesting policies for randomly varying populations will rarely be of the fixed effort or fixed harvest type.

The determination of the mean-variance trade off is only as good as the model that is used in the analysis. However, by providing an easy to understand trade off curve as well as much ancillary information about other characteristics of the policies under consideration, the decision-maker is left in the best position to integrate this knowledge with other information available, both subjective and objective in nature.

ACKNOWLEDGMENT

I am extremely grateful to Chelsea C. White and K. W. Kim for allowing me to see a preliminary version of their paper, and for several invaluable discussions on implementing their algorithm. Mordechai Henig also supplied me with a copy of his Ph.D. dissertation, for which I am grateful.

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TABLE 1.--Block form of the transition matrix.

		$(x_1, z_1) \ (x_2, z_1) \dots (x_N, z_1) \dots (x_1, z_i) \ (x_2, z_i) \dots (x_N, z_i) \dots (x_1, z_N) \ (x_2, z_N) \dots (x_N, z_N)$									
States that have z_1 as optimal harvest	$\left\{ \begin{array}{l} (x, z) \end{array} \right\}$	$\begin{array}{c} \bigcirc \\ \vdots \\ \bigcirc \end{array}$	$\begin{array}{c} \bigcirc \\ \vdots \\ \bigcirc \end{array}$	$\begin{array}{c} \bigcirc \\ \vdots \\ \bigcirc \end{array}$	$\begin{array}{c} \bigcirc \\ \vdots \\ \bigcirc \end{array}$	$\begin{array}{c} \bigcirc \\ \vdots \\ \bigcirc \end{array}$	$\begin{array}{c} \bigcirc \\ \vdots \\ \bigcirc \end{array}$	$\begin{array}{c} \bigcirc \\ \vdots \\ \bigcirc \end{array}$	$\begin{array}{c} \bigcirc \\ \vdots \\ \bigcirc \end{array}$	$\begin{array}{c} \bigcirc \\ \vdots \\ \bigcirc \end{array}$	$\begin{array}{c} \bigcirc \\ \vdots \\ \bigcirc \end{array}$
	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
States that have z_i as optimal harvest	$\left\{ \begin{array}{l} (x, z) \end{array} \right\}$	$\begin{array}{c} \bigcirc \\ \vdots \\ \bigcirc \end{array}$	$\begin{array}{c} \bigcirc \\ \vdots \\ \bigcirc \end{array}$	$\begin{array}{c} \bigcirc \\ \vdots \\ \bigcirc \end{array}$	$\begin{array}{c} \bigcirc \\ \vdots \\ \bigcirc \end{array}$	$\begin{array}{c} \bigcirc \\ \vdots \\ \bigcirc \end{array}$	$\begin{array}{c} \bigcirc \\ \vdots \\ \bigcirc \end{array}$	$\begin{array}{c} \bigcirc \\ \vdots \\ \bigcirc \end{array}$	$\begin{array}{c} \bigcirc \\ \vdots \\ \bigcirc \end{array}$	$\begin{array}{c} \bigcirc \\ \vdots \\ \bigcirc \end{array}$	$\begin{array}{c} \bigcirc \\ \vdots \\ \bigcirc \end{array}$
	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
States that have z_N as optimal harvest	$\left\{ \begin{array}{l} (x, z) \end{array} \right\}$	$\begin{array}{c} \bigcirc \\ \vdots \\ \bigcirc \end{array}$	$\begin{array}{c} \bigcirc \\ \vdots \\ \bigcirc \end{array}$	$\begin{array}{c} \bigcirc \\ \vdots \\ \bigcirc \end{array}$	$\begin{array}{c} \bigcirc \\ \vdots \\ \bigcirc \end{array}$	$\begin{array}{c} \bigcirc \\ \vdots \\ \bigcirc \end{array}$	$\begin{array}{c} \bigcirc \\ \vdots \\ \bigcirc \end{array}$	$\begin{array}{c} \bigcirc \\ \vdots \\ \bigcirc \end{array}$	$\begin{array}{c} \bigcirc \\ \vdots \\ \bigcirc \end{array}$	$\begin{array}{c} \bigcirc \\ \vdots \\ \bigcirc \end{array}$	$\begin{array}{c} \bigcirc \\ \vdots \\ \bigcirc \end{array}$
	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$

where $P_{(x, z)}(\delta^*)$ are the appropriate rows of $P(\delta^*)$ for an optimal policy δ^* .

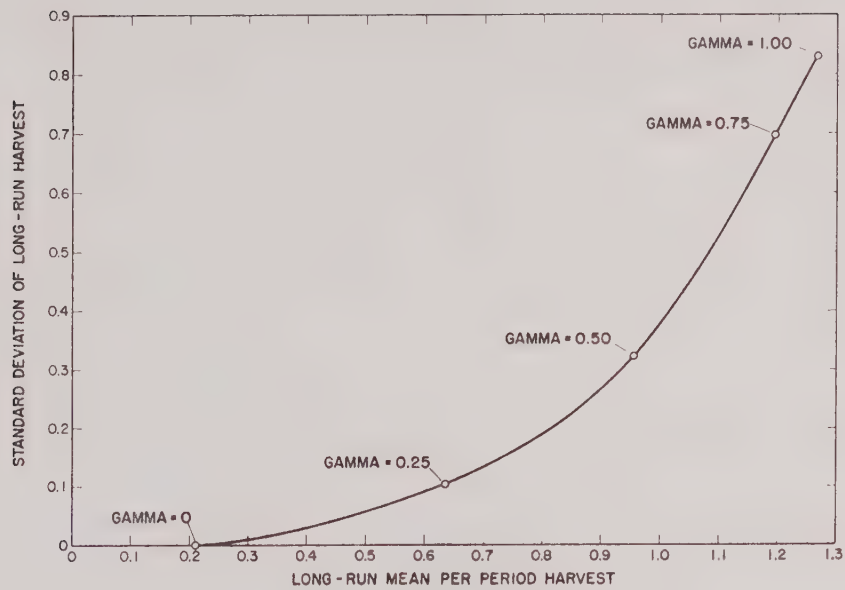


Figure 1.--Long-run (ergodic), mean-standard deviation trade off
for the salmon model.

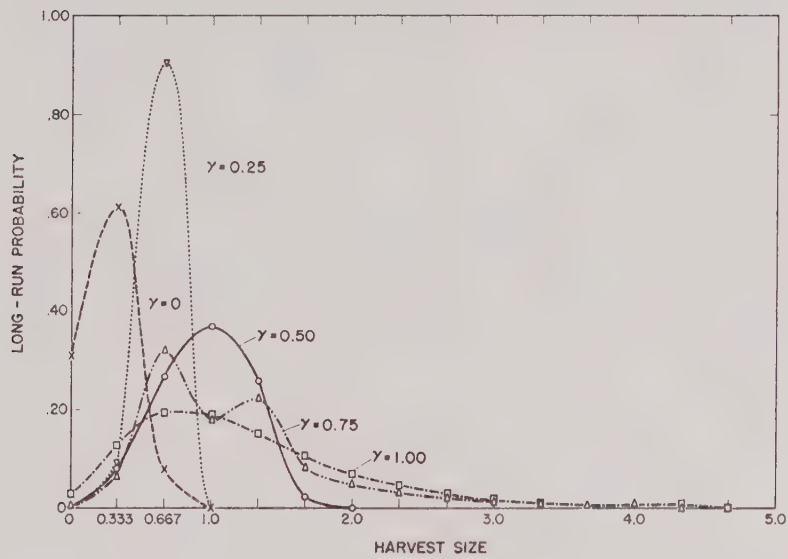


Figure 2.--Long-run (ergodic) distribution for the salmon model
as γ varies.

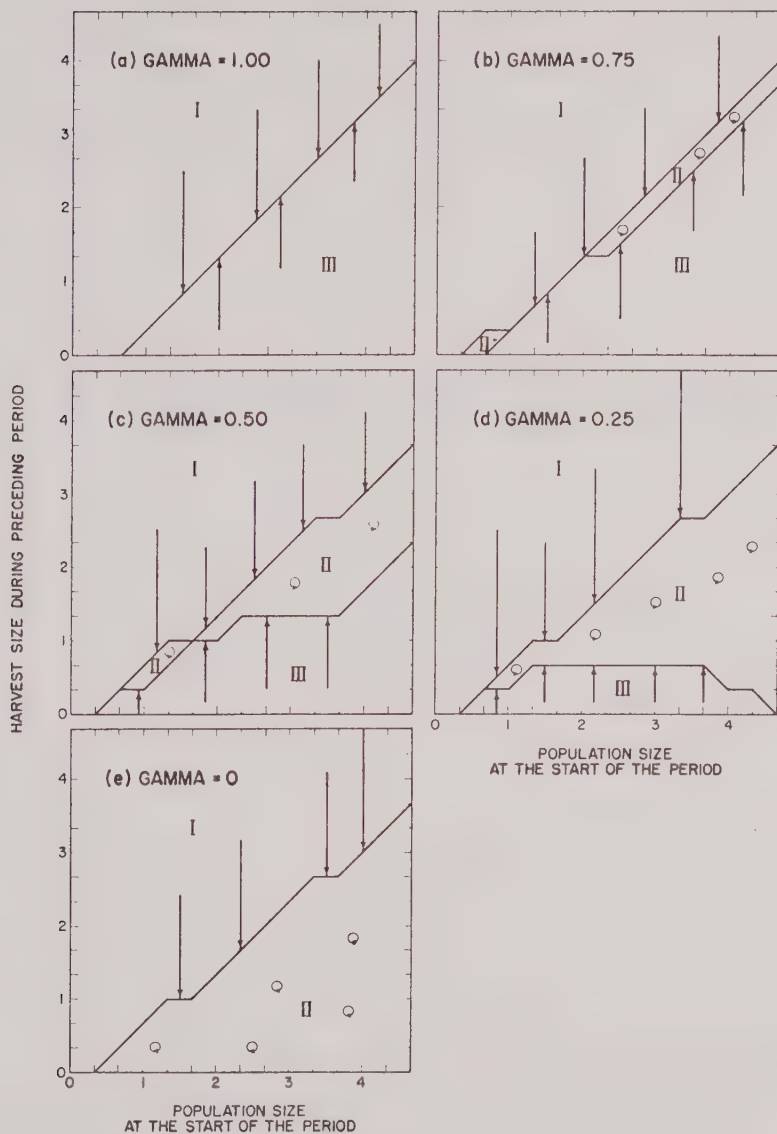


Figure 3.--Optimal policy functions for the salmon model for γ fixed at five levels.

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OBSERVATIONS ON SURFACE-RELEASED, SUBLEGAL SPINY LOBSTERS,
AND POTENTIAL SPINY LOBSTER PREDATORS NEAR NECKER AND NIHOA ISLANDS

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OBSERVATIONS ON SURFACE-RELEASED, SUBLEGAL SPINY LOBSTERS,
AND POTENTIAL SPINY LOBSTER PREDATORS NEAR NECKER AND NIHOA ISLANDS

BACKGROUND

The Insular Resources Task of the Southwest Fisheries Center Honolulu Laboratory is engaged in an extensive survey of the fishery resources of the Northwestern Hawaiian Islands (NWHI). Several projects within the task are directed towards various aspects of spiny lobster, Panulirus marginatus, biology, including distribution, abundance, size composition, growth rate, sexual maturation, and fecundity. These and other data will be the basis of a Fishery Management Plan (FMP) for the developing spiny lobster fishery in the NWHI. Under existing Hawaii law, it is illegal to take berried and undersized spiny lobsters, and lobster fishermen are required to return them alive to the sea after removal from the traps. If the lobsters are released at the surface, they must swim to the bottom at depths which range from approximately 20 to 80 m. Large carangids (probably more than one species) have been observed preying on such surface-released spiny lobsters. Sharks of several species may also be possible predators. Various carangids and shark species are common on the spiny lobster fishing grounds of the NWHI and frequently are numerous around fishing vessels. To determine if regulations governing the way "illegal" spiny lobsters should be returned to the bottom should be written into the FMP, the Western Pacific Regional Fishery Management Council has requested that the Honolulu Laboratory design and conduct experiments to determine the extent of the predation problem and, if the degree of predation warrants, develop and test release procedures that will allow the largest possible percentage of released lobsters to reach the relative safety of the ocean floor.

OBJECTIVE

During the last section of Townsend Cromwell cruise 79-02 (May 27-June 6), observations were made on spiny lobsters and slipper lobsters, Scyllarides squammosus, which were released at the surface from the vessel, and from a bag which had been lowered to the bottom (Table 1). The objectives of the experiments were to determine: (1) The probability of lobsters safely reaching bottom when they are freely released from the surface when potential predators are present, and (2) the vulnerability of lobsters to potential predators when they are released from a bag on the bottom. In addition we anticipated that the observations would provide data on species and size of fishes which might prey on lobsters, and the relationship between lobster size and predator success.

Table 1.--Itinerary of the Townsend Cromwell during spiny lobster predation experiments.

Date 1979	Activity
May 29	- Arrived Necker Island; set lobster traps.
30	- Hauled traps. Conducted lobster release experiments, and made underwater observations 1 mile south of Necker Island.
31	- Hauled traps. Conducted lobster release experiments and made underwater observations 3 miles south of Necker.
June 1	- Hauled traps and made surface observations of released lobsters 4.5 miles northeast of Necker.
2	- Hauled traps. Conducted lobster release experiments and made underwater observations 5 miles northwest of Necker.
3	- Hauled traps. Conducted lobster release experiments and made underwater observations 0.25 mile west of Necker.
4	- Conducted lobster release experiments and made underwater observations 0.2 mile south of Nihoa.

PROCEDURE

The general procedure was: After hauling the traps in the morning, the ship was anchored in a suitable area for the lobster predation experiments. The protective cage was then lowered into the water from the boom and held about 10 ft below the surface. Two underwater observers with a 16-mm movie and Nikonos 35-mm camera then entered the water and descended with the cage to a predetermined depth. On signal from the diver-observers, the surface observers released lots of six lobsters, put over the release bag containing about 20 lobsters, raised or lowered the cage, etc. A "Zodiac" with operator and standby diver maintained position over the underwater observers. The standby diver, with a look-box to monitor the underwater operation, received the signals. The ship-based observers recorded all events that were visible to them from the surface. At the termination of the observational dive (usually determined by air supply or film supply in the movie camera) the divers signaled that they were surfacing.

RESULTS

General Operation

The success of this project largely depended on three factors: (1) The feasibility of handling the cage from the ship, and of underwater observers being able to utilize the cage if required; (2) the availability of sublegal lobsters for use in the experiments; and (3) the successful location of suitable areas where potential predators were present.

Successful deployment and utilization of the cage was dependent on sea and current conditions. During the observations seas ran up to about 2 ft with moderate swells. At times currents of 1 knot or more made it difficult for the divers to maintain position in the vicinity of the cage, make visual observations, and operate the cameras. However, for the most part, the prevailing sea conditions were not limiting to the operations. The vessel's roll did sometimes jerk up and lower the cage over a range of about 5 ft. If shark behavior had made it necessary to routinely use the cage, it would have been necessary to suspend the cage from a buoy at the surface to eliminate the vertical surge from the vessel's roll. As it was, it was not necessary to enter the cage for protection.

The trapping sets were quite fruitful and there was no lack of suitable undersized and berried lobsters for the experiments.

Only the failure to locate areas with substantial numbers of large carangids was limiting during this cruise.

Observations

Table 2 lists the eight observational dives that were made during the cruise. Total underwater time was 148 min. We were able to make underwater observations of surface released spiny lobsters in the presence of several fish species which could be considered potential predators on lobsters: galapagos shark, Carcharhinus galapagensis; gray reef shark, Carcharhinus menisorrh; reef whitetip shark, Triaenodon obesus; white ulua, Caranx ignobilis; omilu, Caranx melampygus; and another ulua, probably Carangoides ferdau.

The lobsters used in the experiments had carapace lengths ranging from about 6.8 to 8.1 cm. On dive No. 1 there were no predators in the area. Four lots of spiny lobsters were released at the surface. The lobsters did not swim to the bottom but fell with their tails curled. On reaching the bottom, they aggregated into small groups on the flat sandy substrate which afforded very little shelter.

Table 2.--Observational dives.

Date 1979	Dive No.	Location	Bottom depth (ft)
May 30	1	1 mile south of Necker	75
31	2	3 miles south of Necker	80
June 2	3	5 miles northwest of Necker	115
2	4	0.25 mile west of Necker	75
3	5	0.25 mile west of Necker	75
3	6	0.25 mile west of Necker	75
4	7	0.2 mile south of Nihoa	65
4	8	0.2 mile south of Nihoa	65

During dive No. 2 there was a 2.2-m galapagos shark swimming in midwater and several jacks, omilu and probably Caranx ferdau on the bottom. Four lots of spiny lobsters were released from the surface. The shark was quite curious about the general operation and the divers but displayed no interest in the lobsters which sometimes passed within 10 ft of it. The lobsters landed on the bottom among the carangids which swam over to investigate but did not touch the lobsters.

Following the underwater observations on dive No. 2 we learned a little more about this particular shark's feeding habits. While the vessel remained at anchor, twice we baited a shark hook with a whole wrasse, Bodianus bilunulatus. The shark readily took the bait, managing to evade capture both times. We then baited the hook with a whole spiny lobster, which the shark would not touch, then with a lobster tail with the same result. The hook was finally baited with a piece of ulua and the shark was caught. Its stomach contained only the two wrasse it had stolen from the hooks. The evidence certainly indicates that even this moderately large and apparently hungry galapagos shark would not prey on spiny lobsters.

On dive No. 3 two lots of spiny lobsters were released. No predators were around, and no useful data were collected.

On dive No. 4 there were numerous omilu (45-60 cm) near the bottom. The bottom release bag (palu bag) weighted with several links of chain weighing about 20 lb and containing 20 spiny lobsters was lowered to the bottom. When the line was jerked to release the slip-knot the bag was lifted up off the bottom and dropped several times, but the bag did not open and we could hear the heavy chain crunching down on the lobsters. When the bag was being raised it opened about 25 ft from the bottom releasing numerous damaged lobsters, their antennae and legs. Three lots of spiny lobsters were released from the surface. The omilu did not show any interest in the lobsters, nor did the lobsters take any evasive action to avoid the fish. The lobsters remained at their landing spot for a short time then moved into one of the numerous holes on this ground.

On dive No. 5 several omilu and a gray reef shark were near the bottom and a small galapagos shark in midwater. The palu bag containing the same chain link weight and 20 spiny lobsters was dropped. As before it did not open on the bottom. It did open about 15 ft up, releasing the lobsters, many of which had lost legs and antennae. Three surface releases of spiny lobsters were made. Neither of the sharks nor the omilu responded to the lobsters. On the third release a single white ulua about 80-90 cm long (perhaps 30-40 lb) came into the area. Two spiny lobsters fell within about 5 ft of the ulua. It showed only mild curiosity but apparently no excitement or predatory behavior. The lobsters continued free falling to the bottom with no tail movements.

On dive No. 6 two gray reef sharks, one galapagos shark, several omilu, and two white ulua were in the general area. A palu bag with a looser slipknot and only a single 3-lb lead weight was dropped with a load of 20 spiny lobsters. The bag opened quickly near the bottom and all of the lobsters escaped without injury. Surface releases of six berried spiny lobsters and one of six slipper lobsters were made. The berried lobsters behaved just as nonberried lobsters had when falling, but seemed to seek shelter more quickly when they reached bottom than nonberried lobsters did. The slipper lobsters, as might be expected, fell through the water column faster than spiny lobsters did, but like the spiny lobsters they fell free with no tail movements. None of the fishes in the area showed anything but casual interest in the free falling lobsters or those released from the palu bag.

On dive No. 7, the first of two made at Nihoa, there were usually two to three reef whitetip sharks and one to three small galapagos sharks in the vicinity. No carangids were seen. A bottom release with the improved palu bag was made with 20 spiny lobsters. The bag opened near the bottom, and most of the lobsters escaped; however, three escaped as the bag was being raised and three arrived at the surface with the bag. A small (125-150 cm) reef whitetip shark was within about 5 ft of the bag when it opened. The shark was quite curious, but showed no predatory interest in the lobsters when they

came out. Eight surface releases including berried spiny and slipper lobsters were made. None of the sharks showed any predatory inclinations.

On dive No. 8, made shortly after the previous dive in the same area, there were three to four small galapagos sharks and three reef whitetip sharks around. A palu bag drop, with 22 spiny lobsters, released nearly all lobsters uninjured at the bottom. The rest came out in midwater. Six surface releases including berried spiny and small slipper lobsters were made. A galapagos shark of about 150 cm did come over and took a close look at the falling lobsters, but did not touch any.

On the morning of June 1, while picking up the last three strings of traps about 4 miles northeast of Necker, there were up to seven 6- to 9-ft galapagos sharks around the ship. These sharks very readily took pieces of lobster trap bait (mackerel) which were thrown overboard. We threw several spiny and two slipper lobsters to them. A number of times the sharks came right up to the lobsters and actually nosed them without taking them. Finally, one shark at a depth of about 20 ft, took a spiny lobster into its mouth. Shortly after a lobster was seen at the surface obviously injured. This was apparently the same lobster that had been taken by the shark, mouthed, and spat out near the surface. Their behavior definitely indicated that these relatively large galapagos sharks were quite hungry. For instance, in addition to eating the mackerel, they tore apart and ate the cardboard cartons in which the mackerel had been packed.

In addition to the visual observations relative to lobster-fish interactions we learned about deficiencies in the palu bag bottom-release system which enabled us to greatly improve its efficiency. Movies and still photos were made of the general operation and fish behavior.

SUMMARY

With the exception of the galapagos shark which (mistakenly) took a spiny lobster into its mouth, none of the fish we observed showed any inclination towards preying on lobsters. Of the fish observed, the data on galapagos sharks and omilu are the most substantial. We had not seriously (due to their size) considered omilu a potential predator on lobsters prior to the experiments and this was corroborated by our observations. Galapagos sharks, which are apparently abundant throughout the NWHI, and certainly were during our observations at Necker, along with tiger sharks, Galeocerdo cuvieri, would both seem to be good candidates as potential lobster predators. This did not prove to be so for galapagos sharks under experimental conditions. Tiger sharks are known predators on lobster. Observations on them would be of value.

Based on somewhat less data, there was no indication that either gray reef sharks or reef whitetip sharks preyed on lobsters.

The three white ulua which were seen in the presence of lobsters certainly did not show any predatory inclinations, but before we can say much about this fish more data are required.

We were unable to make observations on the behavior of schools of large ulua, Caranx ignobilis, and other ulua species or large kahala, Seriola dumerilii, when lobsters were released in their presence. Based on our experience during this cruise, and on word-of-mouth information from participants on previous Townsend Cromwell cruises and commercial vessel cruises to Necker, large schools of carangids rarely if ever occur around that island. If this is so, and considering our observations on sharks, it would appear that surface release of sublegal and berried lobsters by commercial vessels is not likely to be seriously detrimental to the lobster population at Necker Island. This cannot be said for other NWHI areas, such as Maro Reef and Pearl and Hermes Reef, where schools of large carangids are seen more frequently and tiger sharks are probably more abundant.

We learned during this cruise that, given reasonable sea conditions, this type of operation can be efficiently carried out from the Townsend Cromwell. Only a few days of ship time in an area where large carangids and perhaps tiger sharks occur frequently could yield sufficient data to determine whether predation on surface-released lobsters requires further inquiry.

Addendum

Relatively casual observations made during previous Townsend Cromwell cruises in the Northwestern Hawaiian Islands have yielded apparently conflicting information about predation on surface-released lobsters. Two observations recorded in the scientist's log during Townsend Cromwell cruise 77-02 in the spring of 1977 are of interest. One entry reported that northwest of Pearl and Hermes Reef dozens of 25- to 40-kg white ulua were around the traps while the lobsters were being retrieved. When two small spiny lobsters and several small slipper lobsters were tossed back into the water, they were quickly eaten by the fish. On another occasion during the same cruise, while retrieving traps west of Lisianski Island, large numbers of 10- to 30-kg ulua were around the ship. When a small slipper lobster was thrown into the water, the fish merely sniffed it. The records do not indicate whether old bait from the traps was being discarded at the time of these observations or give any information on the state of feeding frenzy, if any, of the fish.

More recently, the National Marine Fisheries Service observer assigned to the commercial fishing vessel Keola during June-July 1979 lobster trapping operations on Maro Reef reported on observations made by himself and crew members of the vessel.

While the Keola was retrieving her traps, old trap bait was continuously disposed of over the side. Simultaneously the observer, who was sampling the lobster catch, tossed the short and berried lobsters back into the sea in the same locality as the discarded bait. During approximately half the time of the operations, large numbers of white ulua and frequently several galapagos sharks were around the vessel. Frenzied feeding was apparent, especially amongst the ulua. On numerous occasions both ulua and sharks were observed to ingest discarded bait and lobsters; however, it was impossible under existing conditions to determine if any lobsters were subsequently spat out.

However, predation was so prevalent that, in an effort to reduce the mortality among the discarded legal lobsters, the procedure was modified. Instead of releasing them while the traps were being retrieved, the lobsters were held in a large tub with flowing water and returned to the sea while the Keola was underway to the next trap site.

Observations such as these seem to indicate that the extent of predation on lobsters released from a vessel may be related to the feeding frenzy of the potential predators. The degree of this frenzy is in turn probably related to variables such as size of the school, size of the fish in the school, feeding state (how close to satiation), and prevailing olfactory and gustatory stimuli. Perhaps even hungry fish require the competition of numbers and/or the strong stimulus of a more favored food such as discarded bait before they will ingest lobsters.

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ANALYSIS OF ENERGY CONSUMPTION OF TUNA SWIMMING IN
CIRCULAR TANKS, AND HAVING ARTIFICIALLY INCREASED
NEGATIVE BUOYANCY

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ABSTRACT

An analysis of the forces acting on fish swimming in curved paths is developed. Calculation procedures to include the influences of centrifugal forces on energy expenditure and swimming speeds are presented. This enables extrapolation of this data collected in round and annular tanks to natural situations.

Also included is an analysis of the changes in swimming speed, metabolic rates, etc., as a result of adding internal weights to negatively buoyant fish.

1. INTRODUCTION

Respiration and swimming speed experiments on tuna are carried out in round tanks at the Kewalo Research Facility of National Marine Fisheries Service (NMFS)/Southwest Fisheries Center (SWFC) Honolulu Laboratory. While this is probably the only test facility in the world capable of sustaining these large, active fish, the prevailing conditions introduce some artifacts which have to be removed, to better simulate behavior in the wild. This report provides a quantitative hydrodynamic analysis of the effects of confinement in round and annular tanks on the fish. A correction factor is introduced which enables simple application of the results obtained in these tanks, to situations in the open ocean. This correction factor shows the increase in thrust the fish has to apply, to stay in a curved trajectory.

Changes in the minimum swimming speeds of negatively buoyant scombrids due to swimming in the circular tank are also calculated, showing an inverse relation to turning radius. Finally hydrodynamic and energetic changes due to inserting weights into the fish are analyzed and equations for the change in thrust and energy requirements are developed.

2. CORRECTION FACTOR FOR SWIMMING IN A CURVED PATH

For a fish swimming horizontally at constant speed the force balance is, in that plane (excluding forces due to buoyancy and its compensation)

$$T = D \tag{1}$$

for swimming in a straight line where T is the thrust and D, the total hydrodynamic drag. Equation (1) describes the force balance in the

tangential direction also for curvilinear motion. However, an additional balance has to be made between the natural centrifugal force driving the fish to stay in a straight line and the countering centripetal force F causing it to remain on a curved path (see Figure 1A). This force is

$$F = \frac{m^1 U^2}{R} = \frac{VU^2}{R} (\rho_f + \rho_w \lambda) \quad (2)$$

where m^1 is the fish virtual mass, ρ_f , the fish density (averaged), V , its volume, U the fish forward speed, λ , the longitudinal added mass coefficient, and R is the instantaneous radius of the curved path. The added mass coefficient λ is multiplied by the density of water ρ_w as the added mass is the volume of water dragged along with the fish. The hydrodynamic drag can be written as (Hoerner 1965)

$$D = \frac{1}{2} \rho_w V^{2/3} U^2 C_{Dt} \quad (3)$$

where C_{Dt} is the total drag coefficient based on the two-thirds power of the volume, as reference area. Here drag includes gill drag, induced drag due to pectoral fin extension and lift, etc. (see Magnuson 1978 for a description of the various components of drag).

To find the relative importance of the centripetal force, we divide (2) by (3), obtaining

$$\frac{F}{D} = 2 \frac{V^{1/3}}{R C_{Dt}} \left(\frac{\rho_f}{\rho_w} + \lambda \right) \quad (4)$$

showing that the fish velocity does not influence the ratio of centrifugal to drag forces. Eq. (4) can now be used to obtain the correction to the force produced by the fish since the total force T_t the fish requires for swimming in a circular path in the horizontal plane is, by vectorial addition

$$T_t = \sqrt{D^2 + F^2} \quad (5)$$

or, dividing by D^2 and applying (1) we obtain the required thrust increase as a function of the correction factor $\frac{F}{D}$.

$$\frac{T_t}{T} = \sqrt{1 + \left(\frac{F}{D}\right)^2} \quad (6)$$

The most complete set of data for estimation of D appears in Magnuson (1978, Table 6) for skipjack tuna. This data will now be used to obtain typical values of the correction factor. The total drag for a 44 cm skipjack tuna swimming at 66 cm/s was estimated there to be 19,780 dynes. The mass of a fish is approximately 1.67 kg (Nakamura and Uchiyama 1966) and with an average density of 1.09 (Magnuson 1978, Table 3), the fish volume is $1,530 \text{ cm}^3$. The drag coefficient C_{Dt} (which is different than Magnuson's drag coefficient because of the different reference area) is found, from equation (3), to be $C_{Dt} = 0.067$ (with $\rho_w = 1.025$).

Magnuson's (1978) data is partially based on the study of ram ventilation by Brown and Muir (1970) which was carried out at the Kewalo Research Facility in Honolulu holding tanks, which are of 7.3 m diameter. These allow a maximum path radius of about 300 cm. Recalling that the longitudinal added mass for a streamlined fish shape is $\lambda \approx 0.2$ (Webb 1975) and substituting the above values into equation (4) we obtain

$$\frac{F}{D} = 2 \frac{(1530)^{1/3} (1.08 + 0.2)}{300 \cdot 0.067} = 1.47 \quad (7)$$

This means that the centripetal force is actually larger than the total drag force under these circumstances. The total force exerted by the

fish swimming in a circular path of 300 cm radius is thus, from equation (6) $\frac{T_t}{T} = 1.78$, i.e., 78% greater than that required for straight swimming at the same speed. The ratio F/D grows essentially proportionally to fish length so that larger fish expend an even greater proportion of energy in swimming in a curvilinear path.

Most other species of fish swim less efficiently than tuna, but being neutrally buoyant, do not have a contribution due to induced drag by the pectorals. This element, which is approximately 30% of the total drag appears only in negatively buoyant fish, so that the total drag coefficient C_{Dt} is changed very little, and the correction factor (4) can be applied to other, not necessarily negatively buoyant species.

3. CHANGES IN MINIMUM SPEED

Negatively buoyant fish, such as most of the scombrids have to swim continuously to maintain a horizontal course, by producing lift. The amount of lift required is equal to the submerged weight, which defines a hydrodynamical minimum swimming speed for horizontal motion (Magnuson 1970). At the minimum speed the pectoral fins produce the maximum possible lift, i.e., the fin's lift coefficient is C_{Lmax} . We can now estimate the influence of swimming in a curved path on the minimum swimming speed (see Figure 1B). Gradual turns during fast swimming are partially produced by banking the pectoral fins (Weihs 1972). Banking the fins reduces the vertical component of the force, since part of the hydrodynamic force is used to turn the fish. But the vertical force is prescribed by the weight, so that the swimming speed must be increased to obtain the required forces. Thus, the minimum swimming speed for

moving in a curved path is always higher than that for swimming along a straight line. This further increases the effort required to swim in circular tanks above and beyond the thrust correction found before (eq. 6).

At the minimum speed U_m

$$W = \frac{1}{2} \rho_w A_f C_{Lmax} U_m^2 \quad (8)$$

where W is the submerged weight of the fish and A_f is the fin lifting area. If the fish has to turn (when it is confined to a round tank) and still wants, for energetic purposes, to stay at minimum speed, the pectoral fins are banked. The force produced on the fins is then (see Figure 1B)

$$P = \sqrt{W^2 + F^2} \quad (9)$$

or

$$\frac{P}{W} = \sqrt{1 + \left(\frac{F}{W}\right)^2} \quad (10)$$

P is produced while the fins are at C_{Lmax} so that

$$P = \frac{1}{2} \rho_w A_f C_{Lmax} U_t^2 \quad (11)$$

where U_t is the minimum speed for a horizontal turn. This is a function of the turning radius, through F (see equation 2).

Substituting (11), (8), and (2) in (10) we have

$$\left(\frac{U_t}{U_m}\right)^2 = \sqrt{1 + \frac{m^2 U_t^2}{RW}} \quad (12)$$

or

$$\left(\frac{U_t}{U_m}\right)^4 = 1 + \frac{2m \left(1 + \lambda \frac{\rho_w}{\rho_f}\right)}{\rho_w R A_f C_{Lmax}} \left(\frac{U_t}{U_m}\right)^2 \quad (13)$$

from which

$$\frac{U_t}{U_m} = \left[B \left(1 + \sqrt{1 + \frac{1}{B^2}} \right) \right]^{1/2} \quad (14)$$

where

$$B = \frac{m \left(1 + \lambda \frac{\rho_w}{\rho_f} \right)}{\rho_w C_{Lmax} A_f} \frac{1}{R}$$

From (14) we see that $U_t > U_m$ for all finite values of R and that the minimum swimming speed grows as the radius decreases. For example, for the skipjack tuna described in Magnuson (1978) and used before,

$m = 1,670$ g, $C_{Lmax} = 1.0$, $A_f = 36$ cm² (Magnuson 1973), $\rho_w = 1.022$,

$\lambda = 0.2$ and $R = 300$ cm again. We obtain $\frac{U_t}{U_m} = 1.094$, i.e., the measured

minimum speed in the round tank is about 10% higher than for the same fish moving in a straight line.

Using the allometric data of Magnuson (1973) we can obtain $\frac{U_t}{U_m}$ as a function of fish size for various species. This appears in Figure 2 for skipjack tuna, for which $m = 0.00490L^{3.36}$ and $A_f = 0.00749L^{2.24}$ so that a slight dependence on fish length is retained, even after normalizing by the length.

The increase in minimum speed also is reflected in the total effort required for swimming in the round tank, as the force goes up as the square of the velocity.

The total thrust increase the fish has to produce is therefore

$$Z = \frac{T_t}{D} \cdot \left(\frac{U_t}{U_m} \right)^2 \quad (15)$$

which for our 44 cm skipjack tuna is $Z = 1.77 \cdot (1.094)^2 = 2.12$ - i.e., over twice the minimum effort in the open sea.

An additional result of the centrifugal forces is the fact that the fish has to make asymmetric motions to produce them. While these motions may be masked by the oscillatory thrust motions, negatively buoyant species such as skipjack tuna will have to maintain a mean banking angle to produce P (equation 9). This angle can be obtained by banking the body and keeping symmetrical fin angles (as in Figure 1B), or by asymmetric deployment of the pectorals. An experimental program to study these angles by photography is underway at the present time. The predicted value of the banking angle (from the vertical) is obtained from (9) as

$$\tan \alpha = \frac{F}{W} \quad (16)$$

$$\tan \alpha = \frac{m(1+\lambda)U^2}{RW} \quad (17)$$

which for the skipjack tuna example above is 12.1° .

4. EFFECTS OF ADDING INTERNAL WEIGHTS TO SKIPJACK TUNA

Adding internal weights to skipjack tuna has been suggested as a means of forcing the fish to swim at higher than their regular volitional swimming speeds. This is required to obtain information on the oxygen consumption of tuna at high swimming speeds. The tuna are expected to swim at higher speeds as they are assumed to be moving at the hydrodynamical minimum speed (i.e., at maximum lift coefficient). Increasing their submerged weight will increase the lift required for

horizontal swimming--and as the fins are already producing the highest lift possible at that speed--the swimming speed has to go up.

For horizontal swimming,

$$L = W \quad (18)$$

where W is the submerged weight, i.e.,

$$W = V(\rho_f - \rho_w) \quad (19)$$

changing the submerged weight to $\tilde{W} = nW$ the lift has to change too, to $\tilde{L} = W$ and therefore $\tilde{L} = nL$ where the curly sign indicates the case of increased submerged weight. From (8)

$$L = W = \frac{1}{2}\rho_w A_f C_{Lmax} U_m^2 \quad (20)$$

and

$$\tilde{L} = nL = \frac{1}{2}\rho_w A_f C_{Lmax} \tilde{U}^2 \quad (21)$$

so that

$$\tilde{U} = \sqrt{n} U_m \quad (22)$$

here the angles of attack and sweep of the pectorals stay the same, and only the speed changes to accomodate the extra weight. Next, we examine the influence of added weights on the drag. The friction and form drag are dependent on velocity squared, therefore, they increase directly proportional to the weight ratio n , i.e.,

$$\tilde{D}_f = nD_f \quad (23)$$

The induced drag, resulting from lift is (Hoerner 1965)

$$D_i = \frac{L^2}{\frac{1}{2}\rho_w U^2 \pi b^2} \quad (24)$$

where b is the fin span

so that

$$\frac{\tilde{D}_i}{D_i} = \frac{\tilde{L}^2 U^2}{L^2 \tilde{U}^2} = \frac{n^2}{n} = n$$

or

$$\tilde{D}_i = n D_i \quad (25)$$

In a similar manner the drag induced by the hydrodynamic forces produced by the caudal fin is, as the mechanism is the same as (25), except the lift is replaced by the thrust

$$\tilde{D}_c = n D_c \quad (26)$$

Finally, the ram drag due to the gill through flow is directly proportional to the swimming speed (Magnuson 1978), i.e.,

$$\tilde{D}_g = \sqrt{n} D_g \quad (27)$$

The gill drag is approximately 20% of the total drag at typical speeds (Magnuson 1978) so that equation (23), and (25-27) can be combined, for the total drag

$$\frac{\tilde{D}_t}{D_t} \approx 0.8n + 0.2\sqrt{n} \quad (28)$$

The rate of working E required to swim at these minimum speeds, which is proportional to the oxygen consumption rate is obtained by

$$E = DU \quad (29)$$

so that

$$\frac{\tilde{E}}{E} = \frac{\tilde{D}\tilde{U}}{DU} = \left(0.8n + 0.2\sqrt{n}\right)\sqrt{n} = 0.8n^{3/2} + 0.2n \quad (30)$$

i.e., the ratio of increase of oxygen consumption grows at a rate slightly less than proportional to the weight ratio to the $3/2$ power. This relationship appears in Figure 3, which serves as a predictor for oxygen consumption rates for weighted fish as the energy requirements appear in the form of a ratio, thereby cancelling out the various transfer coefficients relating oxygen consumption to energy output. This figure also serves as a rough check on whether the fish was swimming at its minimum speed in both cases, as then the ratio of oxygen consumption should be on the curve in Figure 3.

A measured value of this ratio far below the predicted value indicates that the fish was moving at higher than minimum speed when unweighted. Less probable is a measured value higher than the prediction, which would imply that the fish is moving faster than necessary when weighted. Actually, agreement with the predicted oxygen consumption means only that the average lift coefficient for swimming under both weighted and natural conditions is equal, and both could be at above minimum speeds. (This, again is unlikely to occur in practice, due to energy conservation.)

The weighting experiments are carried out to force fish to swim at high speeds, but the information really required is the oxygen consumption at these same high speeds under unweighted (natural) conditions. This can again be obtained approximately by the same type of proportionality analysis. The weights are carried internally by the fish, and so the form and friction drag components are not changed by the presence of

the weight. Gill drag is not changed either, as the speed stays the same. The only component of drag different from equation (28) is the induced drag, as the lift required is now W and not nW . Thus, instead of equation (28), we can write for the ratio of drag at the higher speed D_2 to that at the minimum speed

$$\frac{D_{2t}}{D_t} = 0.5n + 0.2\sqrt{n} + 0.3 \quad (31)$$

The induced drag component is no longer a function of the speed, as the lift stays constant for the unweighted fish see equation (27), and the span is reduced as the swimming speed goes up (by retracting the pectoral fins). Similarly to (30)

$$\frac{E_2}{E} \approx 0.5n^{3/2} + 0.2n + 0.3\sqrt{n} \quad (32)$$

so that we can eliminate the minimum speed energy requirements from (30) and (32) by dividing, i.e.,

$$\frac{E_2}{\tilde{E}} = \frac{0.5n^{3/2} + 0.2n + 0.3\sqrt{n}}{0.8n^{3/2} + 0.2n} \quad (33)$$

which enables an immediate estimate of the unweighted oxygen requirement at elevated speeds, with only the oxygen consumption of the weighted fish, and the submerged weight ratio as input parameters. The values of the ratio $E_2/\tilde{E}$ versus n are plotted in Figure 4. When the fish is unweighted, $n = 1$ and $E_2/\tilde{E} = 1$, while for very heavy weights ($n \rightarrow \infty$) the ratio $E_2/\tilde{E}$ tends asymptotically to 0.625.

Finally, it should be recalled that if the weighted swimming experiments take place in round tanks, the centrifugal corrections of sections 2 and 3 should also be applied.

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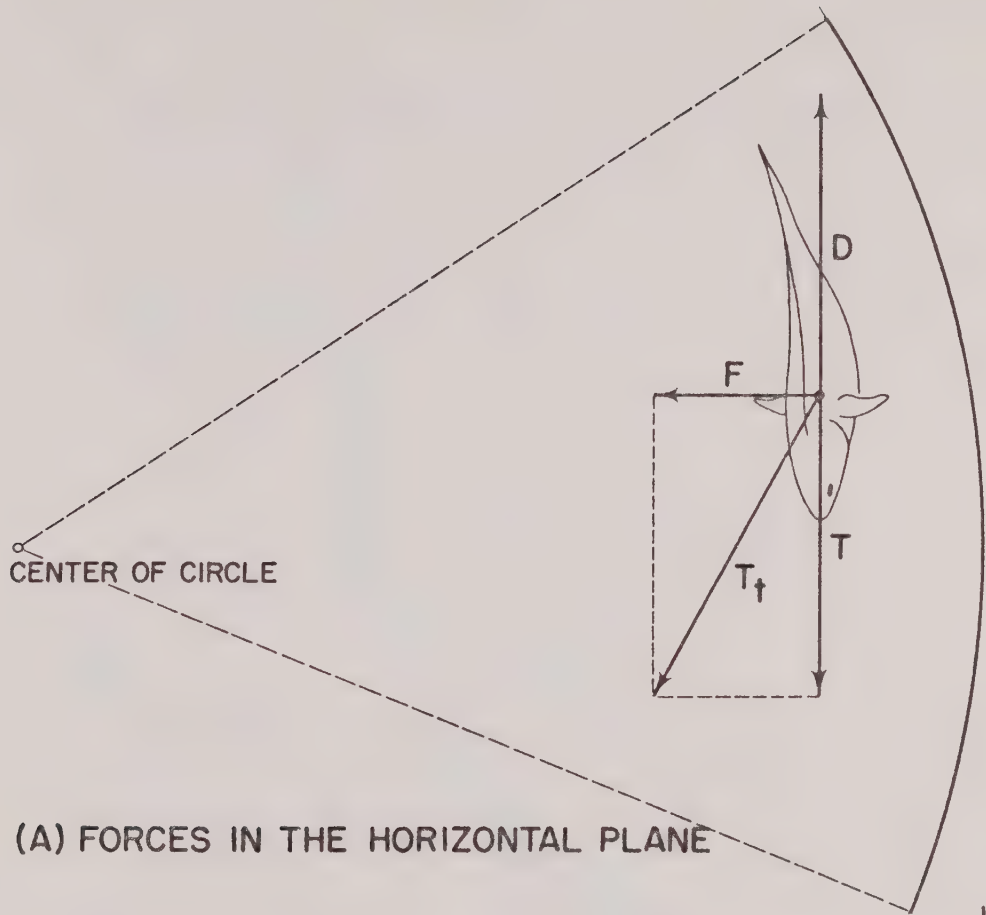
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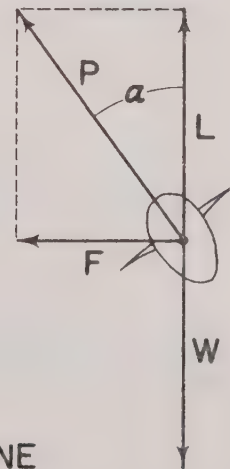
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(A) FORCES IN THE HORIZONTAL PLANE



(B) FORCES IN THE VERTICAL PLANE

Figure 1. Schematic description of forces acting on the fish when swimming in a curved path. A. Forces in the horizontal plane. B. Forces in the vertical plane.

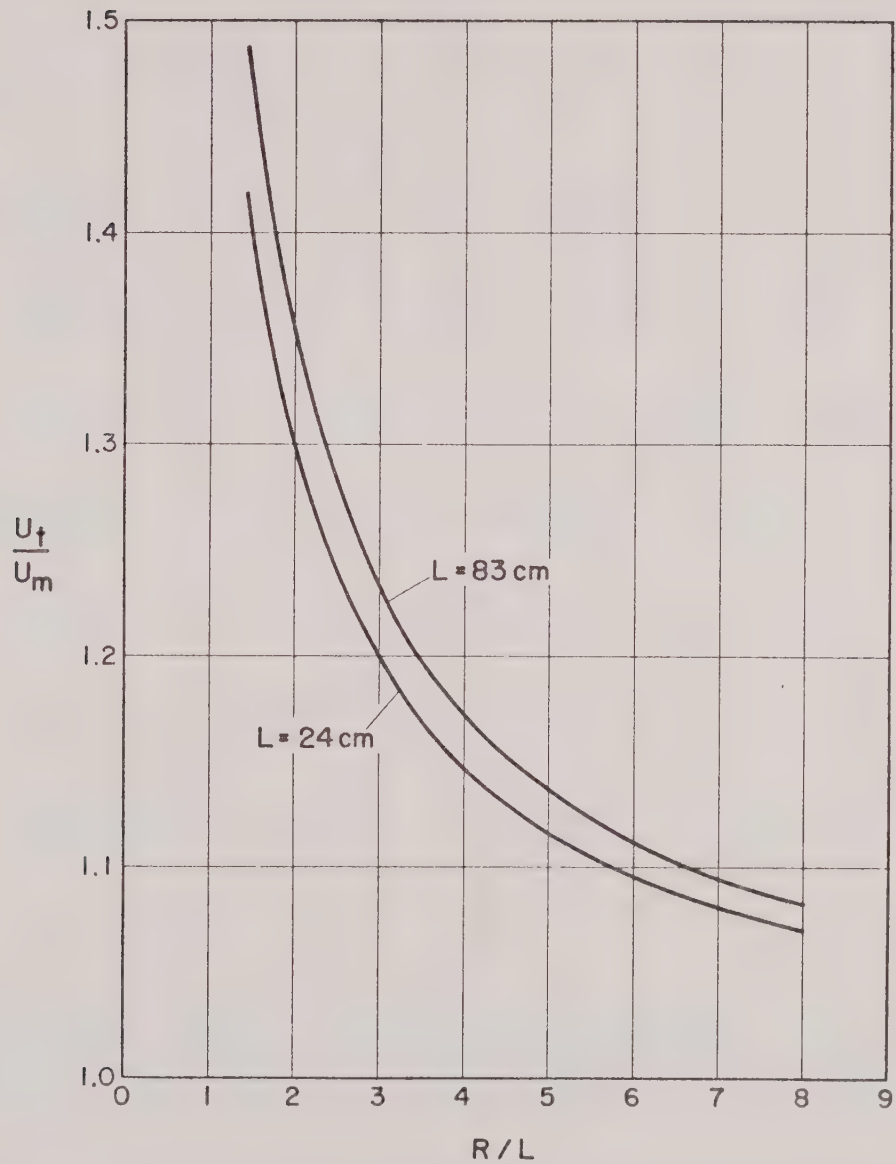


Figure 2. Ratio of minimum speed when moving in a circular path, to the minimum speed in straight-line swimming versus the ratio of turning radius to fish length, for skipjack tuna, Katsuwonus pelamis.

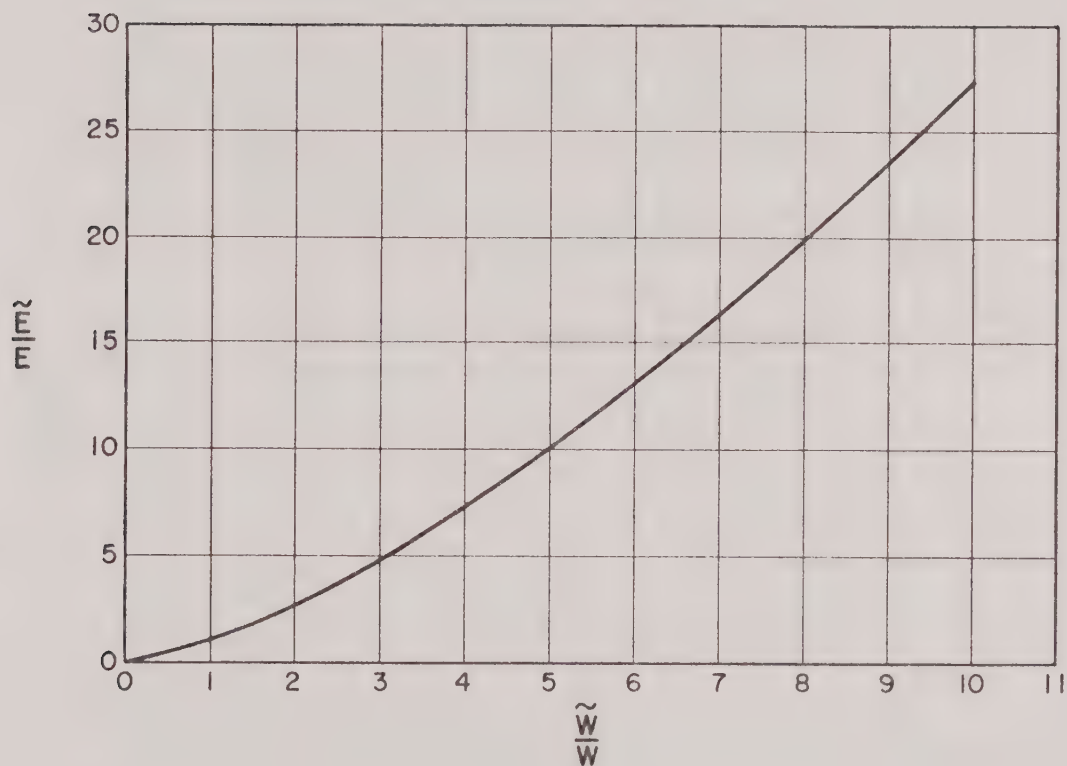


Figure 3.--Ratio of energy (= oxygen) consumption rates for a fish with added weights, to that of the same fish when unweighted versus the ratio of submerged weights of the fish with and without the added weights. It is assumed that the fish is moving at minimum speed in both cases.

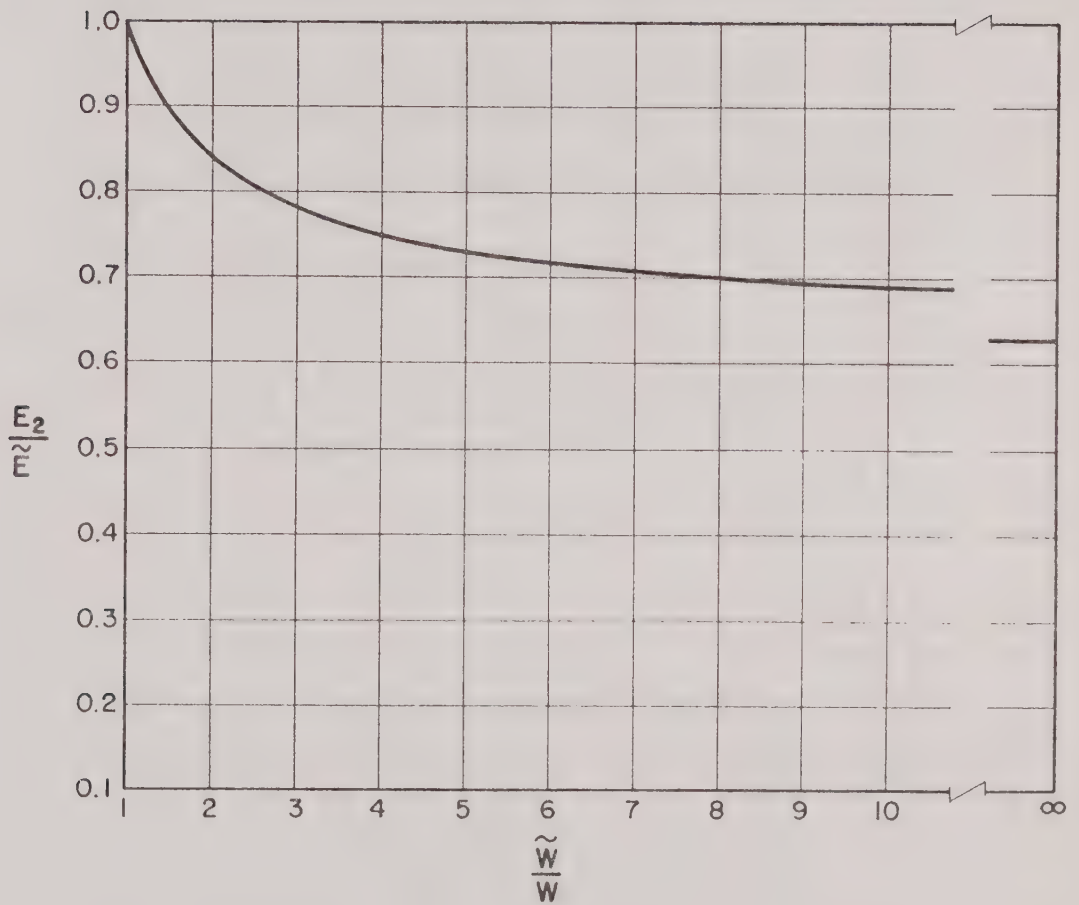


Figure 4. Ratio of energy (= oxygen) consumption rates for an unweighted fish to the rate for the fish moving at the same speed, when weighted, versus the ratio of submerged weights of the fish with and without the added weights.

ANALYSIS OF CATCH AND EFFORT DATA FOR THE
SPINY LOBSTER, PANULIRUS MARGINATUS, AT NECKER ISLAND

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1979

INTRODUCTION

Commercial spiny lobster, Panulirus marginatus, fishing began on a regular basis off Necker Island in the Northwestern Hawaiian Islands in November 1976. Seven commercial fishing vessels from Honolulu reported lobster catches during the period November 1976 through April 1979. Some of these vessels trapped in the area frequently while others trapped only occasionally.

This report analyzes and summarizes commercial and research data for the P. marginatus fishery off Necker Island during the period from November 1976 through April 1979. The commercial data consist of monthly totals of the number of legal lobsters¹ caught and the effort expended (Table 1). These data were collected by National Marine Fisheries Service observers aboard commercial vessels or were reported in catch reports submitted by the vessels' owners. The unit of effort is measured as one baited trap fished on the lobster ground for one night, henceforth referred to as a trap night. The research data consist of total number and effort, as well as length and sex observations, for lobsters caught at sampling sites from the RV Townsend Cromwell.

The island of Necker is surrounded by a large bank (Figure 1). The commercial catch by position indicates that the fishermen have primarily trapped in the northwest region of this bank, indicated as Region I in Figure 1. There were 90,368 legal lobsters trapped in Region I from January 1977 through April 1979; only 17,470 legal lobsters were trapped on the rest of the bank (Region II) during the same period (Table 2). The catch per unit effort (CPUE) in Region II (Figure 2) shows considerable variation, and some of the more recent values for CPUE approach those for Region I (Figure 3). However, because of the lack of a longer series of catch and effort data for Region II, this report will focus only on Region I. By isolating Region I for study, we are making the assumption that the lobster population in this region is closed. This may not be an unreasonable assumption for adult lobsters because tagging experiments indicate minimal migration (Uchiyama²). However, in the case of larval recruitment this may not be the case and for the long term, the assumption of a closed population in Region I may not be valid.

¹A legal lobster is defined as a lobster with a carapace length equal to or exceeding 8.25 cm.

²J. H. Uchiyama. Southwest Fisheries Center Honolulu Laboratory, National Marine Fisheries Service, Honolulu, HI 96812. Personal communication, June 1979.

RELATIVE ABUNDANCE

Catch per unit of effort provides a measure of relative abundance. Changes in CPUE over time can result from changes in population structure and size, as well as changes in fishery methods and gear. In the case of the lobster fishery at Necker between November 1976 and April 1979, the changes in fishing methods and gear have been minimal. A graph of CPUE for legal lobsters from Region I on a monthly basis is presented in Figure 3. Considerable month-to-month variation as well as a declining trend is apparent.

One reason for some of the month-to-month variation in CPUE is that the monthly CPUE is computed by pooling the catch and effort for all the vessels reporting trips to Necker during the month. These vessels are not always the same vessels but a subset of the seven commercial vessels which comprise the fleet.

Catch per unit effort computed on an annual basis has declined each year from 1977 to 1979, although the 1979 figure should be treated with caution because it is based on only an effort of 1,616 trap nights and may change when more 1979 data are available (Table 2).

A regression of CPUE against month, weighted by effort, indicates that at the 5% level the decreasing trend in CPUE for 1977 is significant while the trend in 1978 is not significant. The CPUE for January 1977 and January 1978 represents a sharp increase from the preceding and following months indicating a possible seasonal trend which should be examined as more data become available.

The percentage of legal lobsters in the total lobster catch provides an index of the proportion of legal lobsters in the population to the total lobster population. A decrease in this index could mean that the number of legal lobsters in the population has been reduced and/or the number of sublegal lobsters in the population has increased due to increased reproduction, survival, or immigration. We found that the percentage of legal lobsters in the catch for the RV Townsend Cromwell decreased from 54.2% in November 1976 to 23% in May 1979 (Table 3).

POPULATION ESTIMATES

The primary approach we selected to estimate population size was a method proposed by Allen (1966) (see Appendix 1). Basically, this method consists of a least squares procedure which estimates population size and catchability by minimizing the sum of squares between the actual catch and the predicted catch based on effort.

We used the monthly commercial catch and effort data from November 1976 through April 1979 to estimate population size and catchability. Allen's model assumes natural mortality and recruitment operate in the population. In its most general form, this model assumes that the rate

of natural mortality is constant while recruitment may vary over time. This most general form requires that the user supplies estimates of the natural mortality rate and the recruitment rates. We do not have any size and age data which might allow us to estimate these parameters and consequently, we used a simplified version of Allen's model. We assumed that the ratio of the rate of natural mortality to the recruitment rate ($e^{-M/1-W_1}$) in Appendix 1 is constant. Given effort, we then estimated this constant as the value which gave the best fit of predicted catch to actual catch. We feel the assumption that the ratio, rate of natural mortality to recruitment rate into the fishery is constant, may not be too unreasonable for the 2-year period of our study. If it takes six or more years for a lobster to grow from larval stage to legal size, and if the majority of the mortality occurs during the early years of life, then, even an intense reduction of the population of legal lobsters in 1977 will not have a major effect on the ratio of natural mortality rate to recruitment rate until 6 years later.

The plots of actual monthly catch and predicted monthly catch estimated by Allen's method are presented in Figure 4. The fit of the model to the data is good. Based on this method, we estimate that there were 132,406 legal lobsters in Region I at the beginning of November 1976. This number declined to 68,571 legal lobsters by April 1979. A plot of the monthly estimated population size is given in Figure 5. As could be expected from the catch and CPUE data, the population size of legal lobsters dropped severely during 1977 and decreased very slowly during 1978.

As an independent check on the results obtained by Allen's method, we used two additional population estimation methods which were based on completely different assumptions--Delury's method and Leslie's method (Ricker 1958). Both of these methods are used to estimate population size and catchability in situations where there has been intensive fishing of a closed population over a short period of time. Since these methods apply to fishing over a short period of time, they assume that natural mortality and recruitment are negligible (Appendix 2).

We noticed from Table 1 that trapping was very intense from May through August 1977. We used these data to estimate the population size of legal lobsters at the beginning of May 1977 and the catchability by Leslie's and Delury's methods. The estimated population size and catchability obtained from Leslie's method and Delury's method are in agreement with the estimates obtained by Allen's method (Table 4).

CONCLUSION

The decline in CPUE from 3.95 in 1977 to 3.12 in 1978 strongly suggests that a population size of 65,676 legal lobsters is not sustainable with a CPUE of 3.90. This is further supported by the decline in the percentage of legal lobsters per trap from the Cromwell sampling data. The fact that we do not reject the hypothesis that CPUE did not

decline during 1978, based on the test of the slope of the regression line, suggests that a yield of 21,201 legal lobsters per year may be sustainable with a CPUE of about 3.00. However, if the preliminary indications we have for 1979 are supported with additional data, then, even 20,000 legal lobsters per year would exceed the annual MSY. We can use the result of Allen's model to compute the surplus production which can be harvested without reducing the population size. This value is obtained by multiplying the population size of legal lobsters by the ratio of the natural mortality rate to the recruitment rate for legal lobsters and subtracting the initial population size. We estimated the population size at the beginning of 1979 to be 67,766 legal lobsters and the ratio of the monthly rate of natural mortality to recruitment to be 1.0116. Consequently for 1979, we estimate that slightly over 10,000 legal lobsters can be harvested for the year without reducing the population size of legals. Thus, based on the data presented here, the annual surplus production of legal lobsters in 1979 is estimated to be between 10,000 and 21,000.

It should be noted that we are observing only the short-term effects of exploitation on a previously unexploited population. The long-term population trends as a result of continued exploitation may differ substantially from the results we are now observing.

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Appendix 1

Allen's Population Estimation Procedure

A method developed by Allen (1966) was used to estimate population size at time t (N_t), catchability (q) given effort at time t (X_t) and catch (C_t). M is the natural mortality and W_i is the proportion of the new recruits in the exploited stock for the i^{th} season. The essential relationships of this model are given below:

$$\begin{aligned}
 \text{Year 1} \quad \text{Initial population} &= N_1 \\
 \text{Survival to beginning of next season} &= (N_1 - C_1)e^{-M} \\
 \text{Expected catch} &= \left(N_1 - \frac{C_1}{2} \right) qX_1 \\
 \text{Year 2} \quad \text{Initial population} = N_2 &= \frac{(N_1 - C_1)e^{-M}}{1 - W_2} \\
 \text{Survival to beginning of next season} &= \left[\frac{(N_1 - C_1)e^{-M}}{1 - W_2} - C_2 \right] e^{-M} \\
 \text{Expected catch} &= \left[\frac{(N_1 - C_1)e^{-M}}{1 - W_2} - \frac{C_2}{2} \right] qX_2
 \end{aligned}$$

Continuing in this way we can show that at the beginning of year t the population equals

$$\begin{aligned}
 N_t &= \frac{e^{-(t-1)M}}{\pi(1-W_1)} \left[N_1 - C_1 - \frac{C_2(1-W_2)}{e^{-M}} \dots \frac{C_i \pi(1-W_j)}{e^{-(i-1)M}} \dots \frac{C_{t-1} \pi(1-W_j)}{e^{-(t-2)M}} \right] \\
 &= A_t [N_t - f(C)_{t-1}] ,
 \end{aligned}$$

where

$$A = \frac{e^{-(t-1)M}}{t \prod_{i=2} (1 - W_i)}$$

and

$$f(C)_{t-1} = C_1 + \sum_{i=2}^{t-1} \frac{C_i}{A_i}.$$

Appendix 2

Three Population Estimation Procedures

- 1) Allen's Method.--Estimates population size and catchability by minimizing sums of squares of differences between actual catch and predicted catch given effort. Model incorporates recruitment and natural mortality.
- 2) Delury's Method.--Estimates population size and catchability by fitting equation

$$\ln (C_t/f_t) = \ln (qN) - qE_t,$$

where C_t = catch at time t , f_t = effort at time t , E_t = cumulative effort up to time t , and q = catchability. Model assumes no recruitment or natural mortality.

- 3) Leslie's Method.--Estimates population size and catchability by fitting equation

$$C_t/f_t = qN - qK_t$$

where K_t = cumulative catch up to time t . Model assumes no recruitment or natural mortality.

Table 1.--Catch (No.) and effort (trap night) of legal lobsters at Necker Island.

Date	Region I		Region II		Total	
	Catch	Effort	Catch	Effort	Catch	Effort
<u>1976</u>						
Oct.	107	73	--	--	107	73
Nov.	616	156	--	--	616	156
Dec.	984	276	--	--	984	276
<u>1977</u>						
Jan.	10,030	1,656	1,599	1,081	11,629	2,737
Feb.	--	--	--	--	--	--
Mar.	--	--	--	--	--	--
Apr.	--	--	--	--	--	--
May	15,588	3,480	67	53	15,655	3,533
June	7,132	1,936	461	122	7,593	2,058
July	9,727	2,447	24	75	9,751	2,522
Aug.	5,404	1,832	678	534	6,082	2,366
Sept.	10,524	2,944	293	120	10,817	3,064
Oct.	2,901	916	58	120	2,959	1,036
Nov.	1,885	600	--	--	1,885	600
Dec.	2,485	824	--	--	2,485	824
<u>1978</u>						
Jan.	1,314	254	203	92	1,517	372
Feb.	978	300	--	--	978	300
Mar.	3,687	1,482	54	60	3,741	1,600
Apr.	3,022	719	398	112	3,420	831

Table 1.--Continued.

Date	Region I		Region II		Total	
	Catch	Effort	Catch	Effort	Catch	Effort
<u>1978</u>						
May	3,160	687	--	--	3,160	¹ 687
June	2,940	1,260	--	--	3,849	1,724
July	2,167	603	--	--	2,167	603
Aug.	2,014	585	--	--	2,014	585
Sept.	202	246	--	--	202	246
Oct.	1,574	606	1,373	401	2,947	1,007
Nov.	116	56	5,222	2,349	5,338	2,405
Dec.	--	--	7,040	3,139	7,040	3,139
<u>1979</u>						
Mar.	1,563	658	--	--	1,563	658
Apr.	1,925	958	--	--	1,925	958

¹Two stations with no positions.

Table 2.--Catch (No.) and effort (trap night) data for
legal lobsters, Necker Island.

Year	Catch	Effort	C/E
<u>Region I</u>			
1977	65,676	16,635	3.95
1978	21,201	6,798	3.12
1979 (1/1-5/1)	3,491	1,616	2.16
<u>Region II</u>			
1977	3,180	2,105	1.51
1978	14,290	6,153	2.32
<u>Combined (Regions I and II)</u>			
1977	68,856	18,740	3.67
1978	35,491	12,951	2.74

Table 3.--Townsend Cromwell sampling.

Date	Effort (Trap night)	Percent legals in catch
<u>Region I</u>		
Oct.-Nov. 1976	145	54.2
May 1977	32	40.0
Oct. 1977	116	42.0
Mar. 1978	57	35.0
Oct.-Nov. 1978	104	37.1
May 1979	48	22.8
<u>Region II</u>		
Sept.-Oct. 1977	234	62.6
Mar. 1978	61	81.0
Oct. 1978	52	67.0

Table 4.--A comparison of three population estimation methods.

	<u>Leslie</u>	<u>Delury</u>	<u>Allen</u>
N_{May}	127,000	163,000	125,000
q	3.58×10^{-5}	2.40×10^{-5}	3.94×10^{-5}

N_{May} is an estimate of the number of legal lobsters in Region I beginning May 1977.

q is the catchability coefficient.

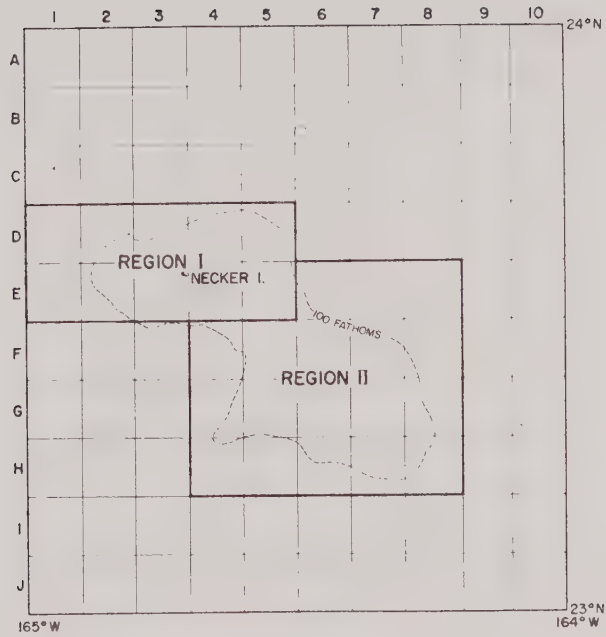


Figure 1.--Necker Bank.

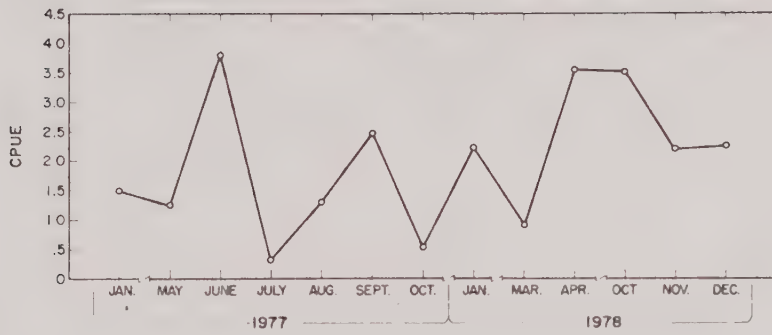


Figure 2.--Catch per unit effort for legal lobsters from Region II at Necker Bank.

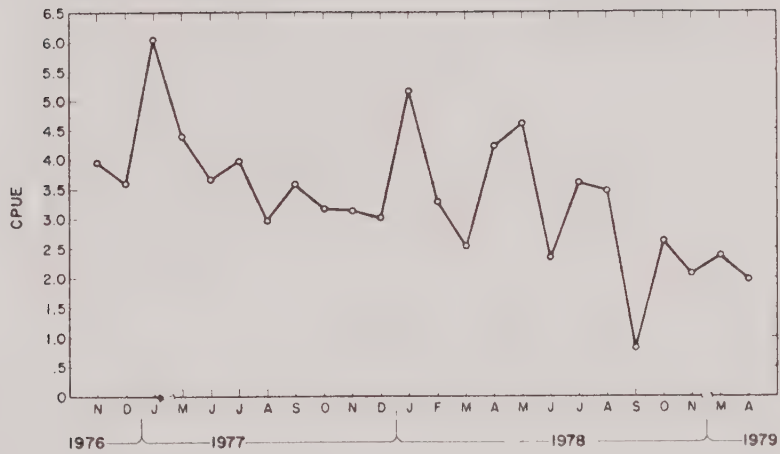


Figure 3.--Catch per unit effort for legal lobsters from Region I at Necker Bank.

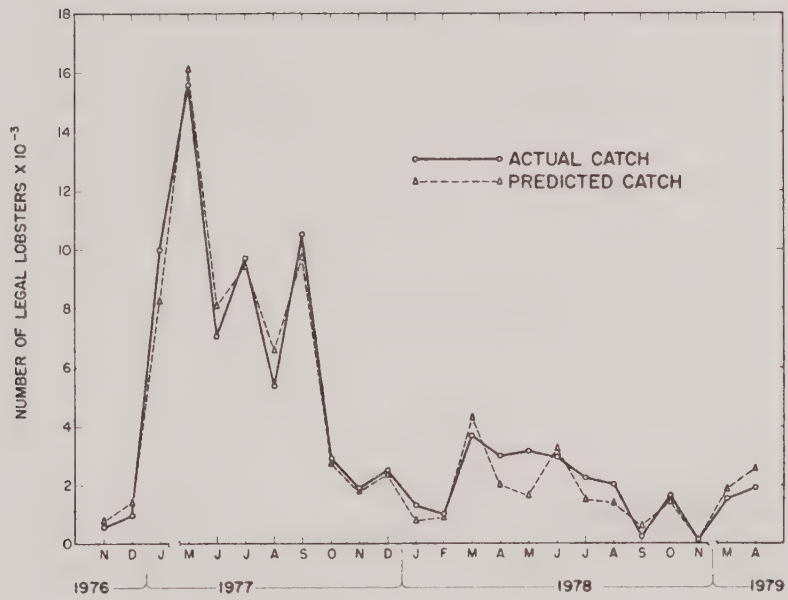


Figure 4.--Predicted versus actual catch of legal lobsters from Region I.

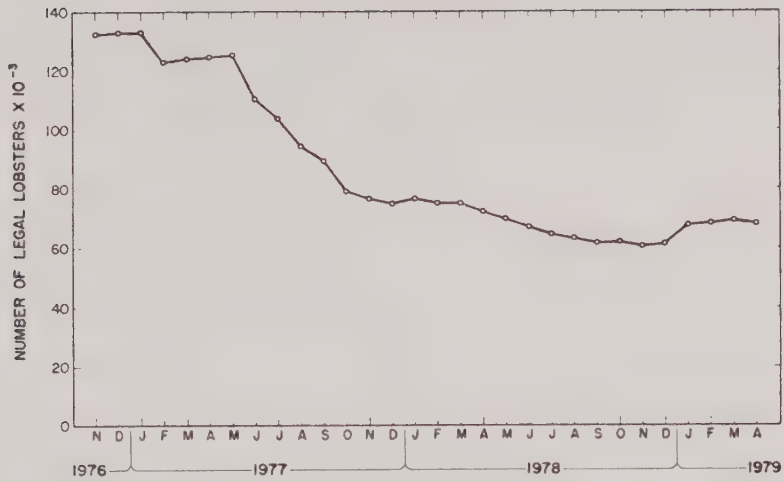


Figure 5.--Estimated population size of legal lobsters in Region I.

Anchored Fish Aggregation Devices in Hawaiian Waters

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INTRODUCTION

The behavior of pelagic fishes to aggregate beneath or near floating objects is being exploited by a number of fisheries. Indonesian fishermen use moored rafts to which palm fronds are attached to attract various clupeids, scombrids, and carangids (Hardenberg, 1950; Soemarto, 1960), the Japanese use moored bamboo rafts to attract dolphin, Coryphaena hippurus (Kojima, 1960, 1966a, 1966b), and Maltese fishermen use anchored cork floats to attract dolphins and pilotfish in the "kannizzati" fishery off Malta (Galea, 1961).

Tunas also have been found to aggregate around floating objects. Japanese pole-and-line fishermen and American live-bait and purse seine fishermen routinely seek out floating logs, masses of drifting seaweed, and other flotsam while fishing for yellowfin tuna, Thunnus albacares, and skipjack tuna, Katsuwonus pelamis (Uda, 1933; Kimura, 1954; McNeely, 1961; Inoue et al., 1963, 1968). Food and Agriculture Organization of the United Nations (FAO) chartered purse seiners working in the Sulu and Celebes Seas also found that successful catches of tunas were almost always made around drifting logs (Chikuni, 1978).

More recently, a method of seining for tunas around large bamboo rafts anchored in calm and extremely deep waters of up to 5,486 m (3,000 fathoms) has been devised and developed in the Philippine tuna fishery (Matsumoto¹). Fishing around these rafts have been so successful that the catch could exceed 100,000 metric tons (MT) in the next year or two, if it has not done so already.

To determine if anchored devices could be maintained in moderate to rough sea conditions and be as effective as those used in calm waters in the Philippines, and to aid the Hawaiian skipjack tuna fishery to increase

¹Matsumoto, W. M. Payao fishing in the Philippines. Manuscr. in prep. Southwest Fisheries Center Honolulu Laboratory, National Marine Fisheries Service, NOAA, Honolulu, HI 96812.

its catch, particularly during the so-called off-season, the National Marine Fisheries Service (NMFS) Honolulu Laboratory (HL) began a program to construct and anchor six fish aggregation devices off the Hawaiian Islands in May 1977, and to monitor the catches around the devices through July 1979. The Pacific Tuna Development Foundation provided financial support for the project with the intention of subsequently funding similar projects in the various Pacific islands, utilizing the knowledge gained from the Hawaiian experiment.

BUOY DESIGN AND METHOD

Background

Studies dealing with the association of fish with various natural and artificial floating objects have been made in the past. Senta (1966) used straw sheaves, straw sheaves tied to bamboo frames, polyvinyl chloride (PVC) strips, straw mats, and artificial seaweed made of palm hair and found no difference among these materials in attracting juvenile fish. Hunter and Mitchell (1968) found that plastic sheets placed horizontally at the surface had greater attraction than those placed vertically and that a tent-shaped configuration was more effective than those horizontally placed. Inoue et al. (1963), obtained data showing that old drift objects were more likely to be accompanied by skipjack tuna, that timber was more successful in attracting skipjack tuna schools than other flotsam, and that timber in the horizontal position was more effective in attracting schools than in the vertical position, but that the catch rate (catch per drift object) of skipjack tuna was slightly better with the timber floating vertically.

The better attributes of both horizontally and vertically floating logs have been incorporated in the Philippine fish aggregation device (Matsumoto, see footnote 1). The device consists of a large bamboo raft, 2.5 x 11 or 12 m, from which two lengths of rope 36 m long are suspended. Palm leaves are attached to the ropes at intervals of 2-3 m. Such rafts have successfully attracted large quantities of tunas and other pelagic fishes.

Types of Devices Used in the Hawaiian Experiment

Two types of fish aggregation devices were used in the Hawaiian experiment. Both types were equipped with fish attractant material suspended from the float, as in the Philippine raft. The attractant material, however, differed from the palm leaves used in the latter, since such palm leaves were not readily available in Hawaii.

The first type was a buoy made of two 208-liter (55-gal) oil drums filled with polyurethane foam and held together in a frame of 7.6 x 7.6 x 0.5-cm (3 x 3 x 3/16 in.) angle iron (Fig. 1). To prevent excessive rotation of the buoy, the angle iron frame was extended below to form a V at the front and rear, to which 2.5 x 10.2-cm (1 x 4-in.) wooden slats were attached. A 13.7-m (45-ft) long drape made of 1.6-cm (5/8-in.) polypropylene rope with a weight at the bottom was hung from the buoy. The drape consisted of 12 lengths of rope hung vertically with cross-members spliced to each at 1.5-m (5-ft) intervals. A pyramid, 0.9 x 1.2 m (3 x 4 ft), at the base and 1.2 m (4 ft) high was built over the drums with a 3.2 x 0.5-cm (1-1/4 x 3/16-in.) angle iron frame and covered over with 0.6-cm (1/4-in.)

plyboard. The pyramid was painted orange and white in alternate horizontal bands and marked A, B, C, etc., according to U.S. Coast Guard requirements. A compartment to house the battery pack, including a hinged door on the rear panel, was built in the upper half of the pyramid. A radar reflector and a light fixture were mounted 1.8 m (6 ft) above the pyramid on a 2.5-cm (1-in.) galvanized pipe. Details of the buoy and radar reflector are shown in Figures 2 and 3.

gs. 2, 3

The buoy was initially anchored with a raft, 0.3 x 0.9 x 6.1 m (1 x 3 x 30 ft) made of 3.8-cm (1-1/2-in.) PVC pipes bolted onto metal frames with floats at both ends, which was tied to the buoy with 18 m (10 fathoms) of 1.6-cm (5/8-in.) polypropylene rope. Six to eight coconut palm fronds attached to a 15.2-m (50-ft) length of cable were suspended from the end of the raft. However, the palm fronds were too fragile and required replacements every 2-3 weeks. The raft also was prone to excessive damage by being banged against the buoy by rough seas. Consequently the raft was removed from the buoy and drapes made of polypropylene rope were used to replace the coconut palm fronds.

The second type of device used was a raft, 1.2 x 3.6 m (4 x 12 ft), made of 5.1 x 15.2-cm (2 x 6-in.) wooden planks bolted top and bottom to four 10.2 x 10.2-cm (4 x 4-in.) crosspieces. The spaces between the top and bottom layers were filled with polyurethane foam. A pyramid and radar reflector-light pole similar to that used on the buoy were mounted on the raft. A drape made of 2.5-cm (1-in.) mesh netting, with 45.7-cm (18-in.) long rope strands attached to it, was hung from the raft (Fig. 4).

g. 4

Anchor and Anchoring Method

A 544.3-kg (1,200-lb) block of concrete was used as the anchor. At one of the six sites where the buoys and rafts were anchored, the currents were strong enough to drag the anchor 2.5 miles over flat bottom.

The anchor line consisted of 1.6-cm (5/8-in.) polypropylene rope with 15.2-m (50-ft) lengths of 1.3-cm (1/2-in.) chain at the top and the bottom. The scope of the line was between 1.6 and 1.7:1. Because polypropylene rope is buoyant, a chain link weight was added to the upper one-fourth to one-third of the anchor line to keep the line from reaching the surface during slack tide. The position of the weight, of course, varied from one buoy to the next, depending upon the length of the line and depth of the site selected for anchoring.

The simplest method was followed in anchoring the devices. The buoy was first set on the water, then the anchor line was payed out, and the anchor was released last in a free fall to the bottom.

BUOY SITES

Four buoy-type fish aggregation devices were initially anchored south of Oahu and southwest of Lanai (Fig. 5) on 9 and 10 May 1977. Buoy A was anchored at a depth of 563 m (308 fathoms), 2 miles from the 914- to 1,829-m (500- to 1,000-fathom) ledge; buoy B at a depth of 443 m (242 fathoms), 1 mile off Penguin Bank, and buoy C at a depth of 450 m (246 fathoms), 1 mile off the tip of Penguin Bank, and buoy D at a depth of 631 m (345 fathoms), 1.1 mile from the 914- to 1,829-m (500- to 1,000-fathom) ledge. The first three buoys were exposed to the northeast trade with winds of 15 to 25 knots and seas as high as 1.2 to

3.6 m (4 to 12 ft), while the last was located in relatively calm waters in the lee of Maui, although at times the seas there could rise to 2.4 m. Buoy A was 16 miles from Kewalo Basin, buoys B and C were 17 and 27 miles, respectively, from Kewalo Basin and buoy D was 10.5 miles from Palaoa Point, Lanai and approximately 65 miles from Kewalo Basin. Buoys B and C were placed off the edge of Penguin Bank to determine what effect the shallow bank (generally 46 to 64 m (25 to 35 fathoms)) had upon the buoys, and buoys A and D were placed near the 914- to 1,829-m (500- to 1,000-fathom) ledge on the basis of reports by trolling boat operators that the best catches of tunas occurred near the 1,829-m (1,000-fathom) drop-off.

Subsequently, on 22 March 1978, two raft-type devices (hereafter called buoys) were anchored off Kona, Hawaii. The first, buoy F, was placed 4.5 miles west of Kaiwi Point at a depth of 2,286 m (1,250 fathoms), and the second, buoy G, was placed 6 miles offshore, 8 miles north-northwest of Keahole Point, at a depth of 402 m (220 fathoms) and 3.5 miles from the 1,829-m (1,000-fathom) ledge (Fig. 5). Both sites were in proven fishing areas for tunas and billfishes.

MONITORING OF BUOYS AND CATCHES

A monitoring and buoy maintaining schedule of one visit per month to each of the four buoys off Oahu and Lanai was set up, with more frequent visits planned at the height of the skipjack tuna season. However, due to prolonged periods of rough sea conditions at the buoy sites and the unavailability of the chartered vessel at critical periods, we were not able to follow the planned schedule.

On all monitoring trips troll fishing was done at the buoy site, and on runs between buoys, all bird and fish school sightings and sightings of scattered birds were noted, and the immediate area around the buoys was scanned with the depth recorder to determine the presence of fish.

Catch data from commercial bait boats visiting the buoys were obtained through interviews and catch forms supplied to all 12 boats comprising the bait boat fleet in January 1978. Catches made during the first 3 months were obtained entirely through interviews. Because of difficulties encountered in interviewing all boat operators on a daily basis and the reluctance of some to disclose where catches were made, the recorded catches and visits to the buoys are considered minimal. The vessels began filling out catch forms in early April, and as the catches around the buoys improved, the reports of visits and catches at the buoys increased sharply near the end of the month and continued through May. Despite this improvement, nearly a third of the fleet neglected to report all trips made to the buoys.

Reports of catches slackened in the latter half of 1978 and none was turned in until May 1979. Although there were extenuating circumstances, such as the presence of large skipjack tuna elsewhere in the fishing area and the losses of buoy A in January and buoy D in March 1979, we learned that occasional visits were made to these buoys before they were lost.

Monitoring trolling boats was even more difficult. It was not possible to monitor visits to the buoys made by all trolling boats since the buoys attracted boats based at outlying harbors and numerous weekend trailer-boat fishermen, who launched their boats from scattered

points. Thus, the collecting of catch and other data was limited to boats based at Kewalo Basin. Even this presented problems because some of the charter boats fished irregularly, going out only when chartered. Consequently, only 15-25 boats were monitored on a near regular basis.

Initial attempts to have the fishermen fill out catch reports were not successful. Therefore, the collecting of fishing data had to be done through interviews with the boat operators.

BUOY PERFORMANCE AND PROBLEMS

All four buoys, A, B, C, and D, initially anchored on 9 May 1977 broke free from their moorings in July, after 7 to 10 weeks. The cause of the mooring line failure was traced to galvanic reaction between the copper fittings and a length of steel cable which had been inserted into the anchor line. All four buoys were reinstalled between August and October 1977 without the cable section and the buoy designation, B was changed to E. A miscalculation in the positioning of buoy E resulted in its loss in December. The buoy was placed too close (1/4 mile) to the edge of Penguin Bank where the bottom rose nearly vertically from a depth of 366 to 46 m (200 to 25 fathoms) and the anchor line could not clear the ledge as the buoy swung over the bank. This buoy was replaced in March 1978.

Since their renewal, the buoys remained in position for a long enough period to prove their effectiveness in attracting fish. Buoys A, E, and D lasted for 16 months, and C remained in position for 20 months. Buoy A was lost in late December 1978, and buoy D in late

February 1979 due to prolonged periods of high wind and sea conditions. Buoys C and E which weathered the storms were finally lost in June and August 1979, respectively. Buoy A was replaced on 31 March, but the others were not because of the closeness to the scheduled termination date of the project (September 1979).

Buoys F and G off Kona, Hawaii were not part of the original buoy program. Consequently, wooden rafts that were available from a prior experiment were used instead of the steel-drum buoys. The rafts were installed on 22 March 1978 and remained operative until January 1979 (a period of 10 months) when they broke apart during the same December-February series of storms that caused the loss of buoys A and D. Buoy F was subsequently replaced by a drum-type buoy on 1 April 1979.

In addition to buoy losses, there was one other problem: vandalism. The radar reflectors and battery compartments on four of the six buoys were shot at with hand guns and were riddled with bullet holes made by hand guns. On two occasions, bullets were found imbedded in the batteries, leading to light failures.

RESULTS

Pole-and-Line Fishing

Although the buoys were deployed in early May, it was not until late fall that modifications to the buoys were completed and the original buoys which had been lost after the first 2-1/2 months were replaced. The timing of the initial deployment coincided with the start of the skipjack tuna pole-and-line fishing season and the bait boats did

not make any serious attempt to fish around the buoys until late December. Visits to the buoys were not reported, as the boats fishing the buoys initially tried to keep their catches from influencing other boats to visit the buoys. We were able to track down at least three catches of over 4.5 MT (10,000 lb) at buoys A and D and one unconfirmed catch of 9.1 MT (20,000 lb) near buoy A in late December.

The number of visits by these and other boats and the reporting of catches improved with time, as the effectiveness of the buoys became known throughout the fleet. The number of known visits increased from a low of 3 in December 1977 to 79 in May 1978, representing 2.4 and 46.2 percent, respectively, of the monthly fishing trips made by the fleet. The ratio of buoy visits to total monthly trips peaked in April when over 53 percent of buoy trips were recorded (Table 1),

The catches around the buoys also increased, correspondingly, from 15.9 MT (35,200 lb) in December 1977 to 192.7 MT (424,897 lb) in April and 193.5 MT (426,515 lb) in May 1978. At the height of fishing around the buoys in April and May, there were 23 catches of over 4.5 MT (10,000 lb), 2 of over 9.1 MT (20,000 lb), and 2 of over 13.6 MT (30,000 lb). One boat reported catching nearly 27.2 MT (60,000 lb) in 3 days of fishing during a 1-week period.

The monthly buoy catches and cannery landings from December 1977 through December 1978 are shown in Figure 6. Both visits and catches decreased drastically in June and remained low throughout the remainder of the year. The decrease in visits was again due to the commencement of the regular fishing season which drew the boats away from the crowded

buoy areas, where at times, 30 or more boats of all types could be seen fishing around a single buoy. The reduced visits to the buoys during the fishing season was influenced also by economic reasons. The large, >6.8 kg (>15 lb), and medium, 4.1-6.8 kg (9-15 lb), fish command a higher price than the small, 1.8-4.1 kg (4-9 lb), and extra-small, <1.4-1.8 kg (<3-4 lb), fish, and fish in the latter two size categories dominated the aggregations around the buoys, although schools of medium fish were often taken there also.

The pattern of visits and catches in 1979 did not follow that of the previous year for several reasons. First, the December-February period was beset with inclement weather with gale force winds that reduced fishing activity; second, the presence of large and medium skipjack tuna in the fishery in late fall and winter months had kept the boats from returning to the buoys; and third, the loss of buoy A in January and the shifting of buoy D in February and its eventual loss in March, eliminated the main sources of attractants for tunas. By the time buoy A was replaced in April and the 1-month period it required to become effective in attracting fish had gone by, the regular fishing season for skipjack tuna was already at hand. This resulted in minimal visits by the fishing fleet in 1979.

The catch at the different buoys varied considerably. Both buoys A and D, which were anchored in deep water and near the 914- to 1,829-m (500- to 1,000-fathom) ledge, were particularly successful in attracting tunas. They commanded 93.9 percent of all buoy visits in 1978 and 90.1 percent of the catches made at the buoys. Buoy C, anchored near

the edge of Penguin Bank and 6 miles away from the 914- to 1,829-m (500- to 1,000-fathom) ledge, was only moderately successful. Most of the catches there were made during a span of 1 to 2 weeks in April, as fishing diminished at buoy A and increased at buoy D. Buoy E, anchored 15 miles away from the 914- to 1,829-m (500- to 1,000-fathom) ledge, fared even worse as only one visit to it was reported. Both buoys E and C received little attention from the pole-and-line boats since the buoys were located too close to the relatively shallow Penguin Bank, where schools of tunas are seen only occasionally. The area, however, is noted for other species such as mahimahi and wahoo (see trolling results).

Troll Fishing

ble 2

Table 2 lists the visits and catches obtained from interviews with boat operators. Only visits to three buoys are included in the table because the fourth buoy, D, was beyond the normal 1-day range of charter boats. Visits to the buoys remained generally low during the last half of 1977 due to the loss of all three buoys in July and August, and the subsequent waiting period of at least a month before the replaced buoys became effective in accumulating fish.

The low visits to the buoys in November and the lack of data in December were due to the absence of project personnel during that period. Owing to the difficulty in contacting all boats and to the reluctance of some boat operators to divulge their catches, the reported visits and catches are greatly understated. Interviews and reports of catches improved from April 1978 when large catches by both trollers

and bait boats at buoy A created a mood of optimism that resulted in enthusiastic reporting of catches among the boat operators. The reduced visits to the buoys during the summer, June through September, were largely due to heavy summer runs of large yellowfin tuna off the coast of Waianae which lured most of the charter boats away from the buoy area.

During the 26 months of buoy fishing by trollers, buoy A was visited most often (51.0 percent) and recorded the most catches (60.7 percent). During the period April through June 1978, buoy A accounted for nearly 70 percent of the year's catch as a result of the accumulation of tunas which also attracted marlins and spearfish, the primary targets of the charter boats.

Buoys B and C were visited less often (26.4 and 22.6 percent, respectively), however several boats that preferred trolling for mahimahi made regular visits to these buoys. Although buoys B and C were not productive of tunas, they were ideally placed to attract mahimahi from the nearby Penguin Bank. During 1978 the catch rate of mahimahi at these two buoys was 2.42 fish per visit as compared with 0.83 fish per visit at buoy A. In 1979 the difference was even greater, 1.73 fish per visit at buoys B and C versus 0.48 at buoy A.

The species composition of fish taken at the buoys presents an interesting picture (Fig. 7). Despite the heavy fishing for tunas at buoy A, the mahimahi catch was the highest in all 3 years. The absence of buoy A during the first 3 months in 1979 definitely affected the tuna catch total, but if 1978 is a good example, the mahimahi probably would still not have been replaced as the principal species taken. It should be noted

here that although catches of mahimahi were reported most frequently, it was not the dominant species in terms of number, as seen from the massive catches of skipjack tuna by the bait boats in 1978.

Heavy activity of trolling boats around the buoys usually began about 3 to 4 weeks after the buoys had been deployed. Prior to this time, one or two boats would make occasional visits to the buoys to inspect the buildup of fish around the buoys. As activity around the buoys picked up, fishing at times became hectic. During the second week in April 1978, when the area around buoy A was teeming with large schools of skipjack tuna and birds in the hundreds were seen everywhere from the buoy out to a radius of 1-1/2 or 2 miles, no less than 15 trollers were seen fishing within 3 miles of the buoy. During this period one troller reported a catch of 50 skipjack tuna weighing 4.1-4.5 kg (9-10 lb) each, a second reported 80 skipjack tuna, and a third, 25 skipjack tuna and a 113.4-kg (250-lb) blue marlin, all on the same day.

Occasional reports from Maui indicated similar fishing activity around buoy D where individual boat catches of 136.1-317.5 kg (300-700 lb) of skipjack and yellowfin tunas and 45.4 kg (100 lb) of mahimahi per weekend were commonly made in April 1978. One boat from Lanai reported catching 226.8-453.6 kg (500-1,000 lb) of yellowfin tuna on each visit to the buoy, releasing all the 3.6-4.5 kg (8-10 lb) skipjack tuna caught to reserve boat space for the larger 13.6-22.7 (30-50 lb) yellowfin tuna.

Other reports from Kona, Hawaii indicate the effectiveness of the buoys. Buoy F was anchored in May at a depth of 2,286 m (1,250 fathoms) at the edge of an outstanding fishing area. By July, it was teeming with 1.4-4.5 kg (3-10 lb) skipjack and yellowfin tunas, and with marlin. The trollers could run to the buoy and in 10-15 minutes pick up small skipjack tuna, which they used as bait for marlin fishing, and begin fishing for marlin immediately instead of losing nearly half-a-day or more, as they were accustomed to, before the buoys were installed. In the height of the summer marlin run, some trollers which took advantage of easy catches of bait-size skipjack tuna around the buoy were reporting catches of 10-11 marlins in 10 days, while others were reporting catches of 3 and 4 marlins a day.

Other Types of Fishing

The buoys off Kona, Hawaii also attracted many commercial skiff fishermen using the "drop stone" method to fish for yellowfin tuna. In this type of fishing, a large 25.4-30.5 cm (10-12 in.) long mackerel scad is used as bait. The bait is laid on a smooth stone weighing about 0.9 kg (2 lb) together with a package of chopped up mackerel scad wrapped in ti leaves and both bait and chum package are bound to the stone by a few turns of the mainline, and secured by a slip knot. The stone is lowered 55 to 110 m (30 to 60 fathoms) and is jerked free to expose the bait and chum. Normally, this type of fishing is done at night for yellowfin tuna weighing 45.4-113.4 kg (100-250 lb) or more. Because of the buoys, however, these fishermen were able to fish for large porpoise-associated yellowfin tuna during daylight.

This type of fishing is done by positioning the skiff in the path of porpoise herds, which circled the buoy at a distance of 3 to 5 miles.

The lines are set to catch the yellowfin tuna accompanying the porpoise as the porpoise herds approach the skiff. Prior to the placement of the buoys, the porpoise herds were known to move out of the area in a day or so but now they tended to remain in the area for longer periods enabling these fishermen to fish on a daily basis.

One report in June 1978 indicated that up to 50 boats fishing off buoy G brought in 15.9 MT (35,000 lb) of yellowfin tuna and marlin on one weekend. The "drop stone" skiffs reportedly averaged three to four yellowfin tuna per day in this period.

DISCUSSION

The daily catch records during April and May 1978 provided interesting information about the fish aggregations attracted to the buoys. First, the record of consecutive days successfully fished at a buoy gives a rough idea of the fish-holding quality of the buoy. During this period, fish were caught at buoy A on 2, 3, 5, and 10 successive-day periods. The longest fish-holding period consisted of 2 successful days, a blank day, followed by 10 successful days, a blank day, and by 2 more successful days. At buoy D fish were caught on 2, 4, and 10 successive days, the last 2 separated by a blank day. It cannot be stated definitely whether the single blank day between periods of consecutive successful days was really devoid of fish or whether the boats fishing that day at the buoys failed to report the catches. Because we know that reporting of catches was not followed diligently by all boats, the latter would seem more likely. Thus, we can say that the tuna schools remained in the buoy area for periods of up to 2 weeks at a time.

Second, on 12 days during the 2-month period, three to five boats reported catches from the same buoy, which suggested that more than one fish school may have been present around the buoy at the same time. Interviews with trolling boat operators and our own observations of bait boat activity around the buoys support this, as on several occasions we noted two or three bait boats fishing on opposite sides of a buoy at distances of up to a mile from the buoy. Whether these were schools that had broken away from a single large school was not determined, but this was possible.

Third, the total aggregate of fish caught over consecutive days could represent fish from a single school. At buoy A, the catches of 3, 5, and 16 consecutive days were 35.9 MT (79,084 lb), 22.0 MT (48,455 lb), and 63.0 MT (138,689 lb), respectively. At buoy D, the 15-day catch was 155.7 MT (342,717 lb). These totals are comparable with the purse seine catches made in the Philippine payao (raft) fishery (Matsumoto, see footnote 1), where catches of 20 to 40 MT per set from individual rafts are quite common and catches of up to 200 MT are made occasionally.

It is not possible to determine accurately what the total catch might have been without the buoys in 1978, nor to what extent the buoys had increased the catch during the off-season winter months, because both monthly and annual catches in the fishery fluctuate widely from season to season. There is no question, however, that the buoys were a boon to the pole-and-line fishermen. Interviews with fishing boat skippers revealed:

1) That the buoys greatly reduced scouting time and time lost in the pursuit of distant schools, since the schools tended to remain in the vicinity of the buoys.

2) That they could head directly to the buoys and be assured of some catch (a catch as small as 453.6 kg (1,000 lb) is sufficient to pay for a week's supply of fuel for some boats).

3) That they could risk making trips with (a) inferior bait species, (b) baitfish in slightly weakened condition, or (c) a bait supply far less than that required for a regular trip. The need for less bait and the proximity of buoy A to Kewalo Basin have enabled some boats to fish 5 or 6 days a week, where previously they would require 3 to 4 days to catch bait. During April 1978, at the height of activity at the buoys, one boat had fished on 8 out of 9 days.

The buoy test, which was aimed primarily to aid the skipjack tuna fishery, resulted in two important side benefits. One was the heavy use of the buoys by trolling boats. Many of the trollers, while engaging in sport or recreational fishing, nevertheless, sell their catch to fish markets. Others fish strictly on a commercial basis. The combined catches of these boats could add significantly to the State of Hawaii's total fish production. Interviews with both charter and commercial trolling boat operators indicated that the buoys greatly reduced the number of zero-catch days.

The other was the utilization of the buoys by the "drop stone" commercial fishermen. This method of fishing is normally done at night, but in Kona, the presence of the buoys made it possible for these

fishermen to operate during the day also. This type of fishing is also done off Hilo, Hawaii where squid is used as the principal bait, supplemented by mackerel scad, and is known as the "ika-sibi" fishery (Yuen, in press). The term "ika-sibi," of Japanese origin, literally translates to "squid tuna" and was coined to describe the Hilo-Kona-based fishery. The fishery, which began in 1973, shows promise of becoming an important segment of Hawaiian fisheries. The catch, consisting of bigeye and yellowfin tunas and albacore, increased from 89.0 MT in 1973 to 154.6 MT in 1975. This fishery could be bolstered greatly by the use of fish aggregating buoys.

SUMMARY AND CONCLUSION

Fish aggregation buoys tested in Hawaiian waters proved effective in attracting tuna schools and in holding the schools in the vicinity for periods of up to 15 or 16 days, long enough to permit the commercial bait boats to harvest the fish with minimum expenditures of baitfish and fishing time. The test also showed that buoys could be placed and utilized in areas with moderate to rough sea conditions.

Additional benefits from the buoys were their usefulness to both commercial, recreational, and charter boat operators. The buoys reduced the number of zero-catch trips by the trollers.

The buoys off Kona, Hawaii also benefitted the handline fishery for large yellowfin tuna by permitting daytime fishing, as well as the normal night operations.

The success of the buoys in attracting fish has prompted the State of Hawaii Division of Fish and Game to plan and implement a statewide buoy system which will go into effect in the fall of 1979. The buoy system will include at least 26 buoys which will be distributed around the major islands in the State.

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Table 1.--Monthly catches of skipjack tuna from buoy areas (in pounds).

Year Month	Buoy										No. of trips	Catch per trip	Buoy visits as % of total trips	Buoy catch as % of cannery landings		
	A		E		C		D		Totals							
	Catch	Visits	Catch	Visits	Catch	Visits	Catch	Visits	Catch	Visits						
1977																
Dec.	10,000	1	--	--	--	--	25,200	2	35,200	3	11,733.3	226,622	126	1,798.6	2.4	15.5
1978																
Jan.	9,000	2	--	--	--	3	13,938	4	41,538	9	4,615.3	410,210	160	2,563.8	5.6	10.1
Feb.	7,849	7	--	--	--	2	40,091	20	49,336	29	1,701.2	143,522	111	1,292.9	26.1	34.4
Mar.	9,718	6	--	--	--	--	22,872	14	32,590	20	1,629.5	142,646	69	2,067.3	29.0	22.8
Apr.	86,738	14	5,110	1	88,734	9	244,315	34	424,897	58	7,325.8	727,933	109	6,678.3	53.2	58.4
May	203,675	47	--	--	--	--	222,840	32	426,515	79	5,398.9	996,312	171	5,826.4	46.2	42.8
June	31,500	7	--	--	--	--	--	--	31,500	7	4,500.0	909,456	183	4,969.7	3.8	3.5
July	28,109	9	--	--	--	--	--	--	28,109	9	3,123.2	869,491	166	5,237.9	5.4	3.2
Aug.	--	--	--	--	--	--	23,170	5	23,170	5	4,634.0	571,981	125	4,575.8	4.0	4.1
Sept.	--	--	--	--	--	--	30,725	9	30,725	9	3,413.9	251,363	80	3,142.0	11.2	12.2
Oct.	--	--	--	--	--	--	22,882	9	22,882	9	2,542.4	341,885	97	3,524.6	9.3	6.7
Nov.	--	--	--	--	--	--	34,162	12	34,162	12	2,846.8	471,969	107	4,410.9	11.2	7.2
Dec.	--	--	--	--	--	--	--	--	--	--	--	218,450	76	2,874.3	--	--
Totals	376,589	92	5,110	1	108,730	14	654,995	139	1,145,424	246	41,731.0	6,055,218	1,454	47,163.9	205.0	205.4

Table 1.--Continued.

Year Month	Buoy										No. of trips	Catch per trip	Buoy visits as % of total trips	Buoy catch as % of cannery landings	
	A		E		C		D		Totals						
	Catch	Visits	Catch	Visits	Catch	Visits	Catch	Visits	Catch	Visits					
1979															
Jan.	(Buoy lost)		--	--	--	--	--	--	--	--	47	2,405.3	--	--	
Feb.			--	--	--	--	--	--	--	--	74	2,980.3	--	--	
Mar.			--	--	--	--	(Buoy lost)			--	74	3,494.7	--	--	
Apr.	(Buoy replaced)		--	--	--	--				--	109	2,574.9	--	--	
May	10,500	5	--	--	--	--				10,500	5	2,100.0	1,045,667	2.8	1.0
June	18,841	5	--	--	--	--	(Buoy lost)			18,841	5	3,768.2	827,293	2.7	2.3
July	4,200	3	--	--	--	--				4,200	3	1,400.0	1,012,239	1.6	0.4
Aug.	(Buoy lost)		(Buoy lost)							--	--	--	--	--	--
Totals	33,541	13	--	--	--	--	--	--	--	33,541	13	7,268.2	3,758,064	7.1	3.7

Table 2.--Fish caught by trolling boats based at Kewalo Basin.

Buoy	A			B/E			C			All buoys			
	Year	Catch		Visits	No. of fish	Wt.	Visits	No. of fish	Wt.	Visits	Catch		
		Month	No. of fish								No. of fish	Wt.	
(Buoys anchored on 9 May)													
1977													
May													
June	8	18	475	3	0	0	4	1	5	15	19	480	1.26
July	--	--	--	5	57	335	1	11	55	6	68	390	11.33
Aug.	2	0	0	--	--	--	--	--	--	2	0	0	0.00
Sept.	2	4	25	--	--	--	--	--	--	2	4	25	2.00
Oct.	12	18	187	7	22	170	1	0	0	20	40	357	2.00
Nov.	2	1	10	2	3	40	1	0	0	5	4	50	0.80
Dec.													
Totals	26	41	697	17	82	545	7	12	60	50	135	1,302	2.7
1978													
Jan.	9	64	351	--	--	--	7	49	415	16	113	766	7.06
Feb.	9	29	216	--	--	--	7	3	26	16	32	242	2.00
Mar.	6	6	272	--	--	--	5	3	50	11	9	322	0.82
Apr.	14	236	2,499	3	5	84	6	38	395	23	279	2,978	12.13
May	19	294	4,083	8	23	363	9	129	992	36	446	5,438	12.39
June	6	35	431	4	32	452	4	33	591	14	100	1,474	7.14
July	7	45	1,340	1	2	16	2	4	42	10	51	1,398	5.10
Aug.	11	14	327	1	7	42	5	17	148	17	38	517	2.24
Sept.	5	17	1,001	1	2	38	--	--	--	6	19	1,039	3.17
Oct.	31	26	953	8	9	152	12	6	105	51	41	1,210	0.80
Nov.	37	33	210	8	10	135	6	6	165	51	49	510	0.96
Dec.	3	10	250	8	1	6	6	2	15	17	13	271	0.76
Totals	157	809	11,933	42	91	1,288	69	290	2,944	268	1,190	16,165	4.44

(Buoys anchored on 9 May)

(No data)

Table 2.--Continued.

Year Month	A			B/E			C			All buoys		
	Visits	Catch		Visits	Catch		Visits	Catch		Visits	Catch	
		No. of fish	Wt.		No. of fish	Wt.		No. of fish	Wt.		No. of fish	Wt.
1979												
Jan.	--	--	--	11	18	189	10	21	205	21	39	394
Feb.	--	--	--	37	69	1,705	15	18	322	52	87	2,027
Mar.	--	--	--	16	15	180	12	4	48	28	19	228
Apr.	10	4	51	7	11	144	8	14	171	25	29	366
May	59	189	2,582	15	36	594	15	61	2,076	89	286	5,252
June	27	136	1,551	6	22	434	1	3	60	34	161	2,045
July	30	45	1,315	9	25	257	--	--	--	39	70	1,572
Totals	126	374	5,499	101	196	3,503	61	121	2,882	288	691	11,884
Totals for entire period	309	1,224	18,129	160	369	5,336	137	423	5,886	606	2,016	29,351
Percent of total for all buoys for entire period	51.0	60.7	61.8	26.4	18.3	18.2	22.6	21.0	20.0			3.33

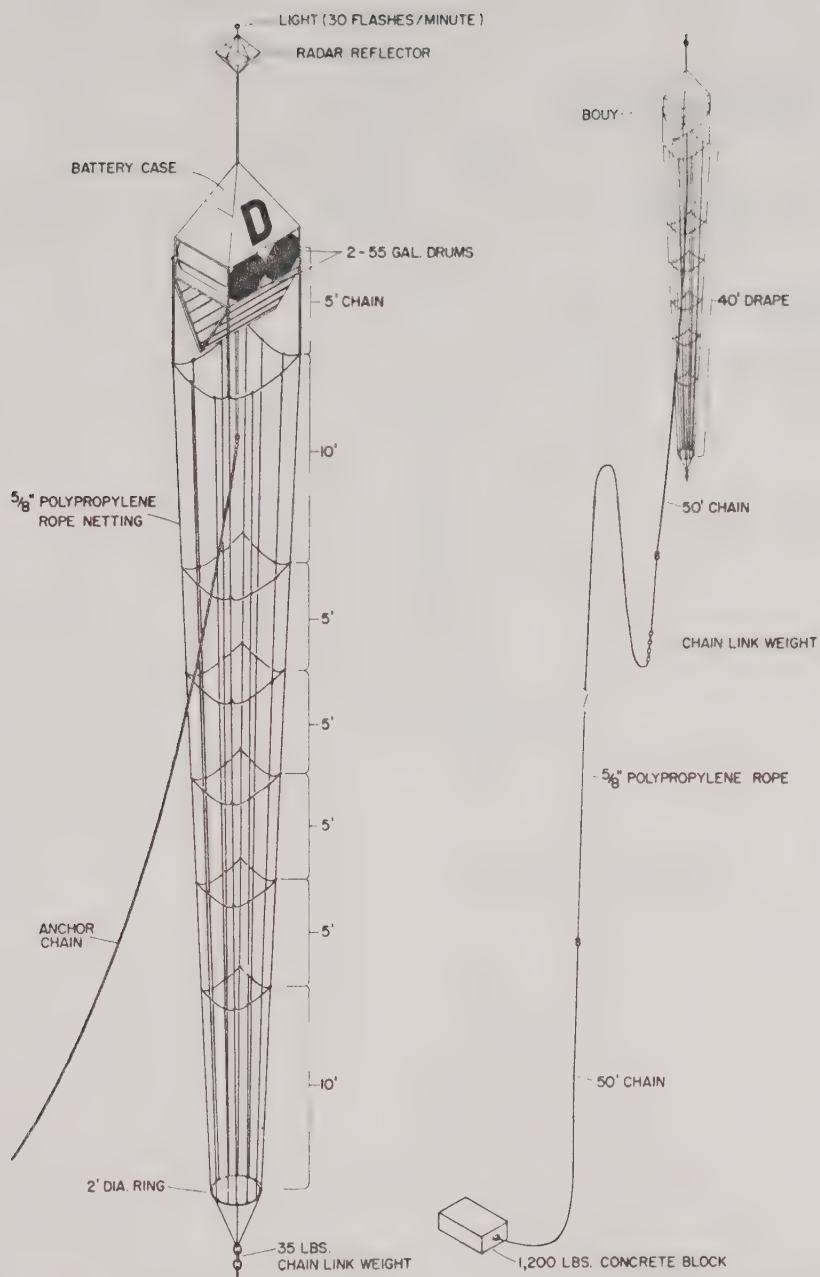


Figure 1.--Fish aggregating device, buoy type.

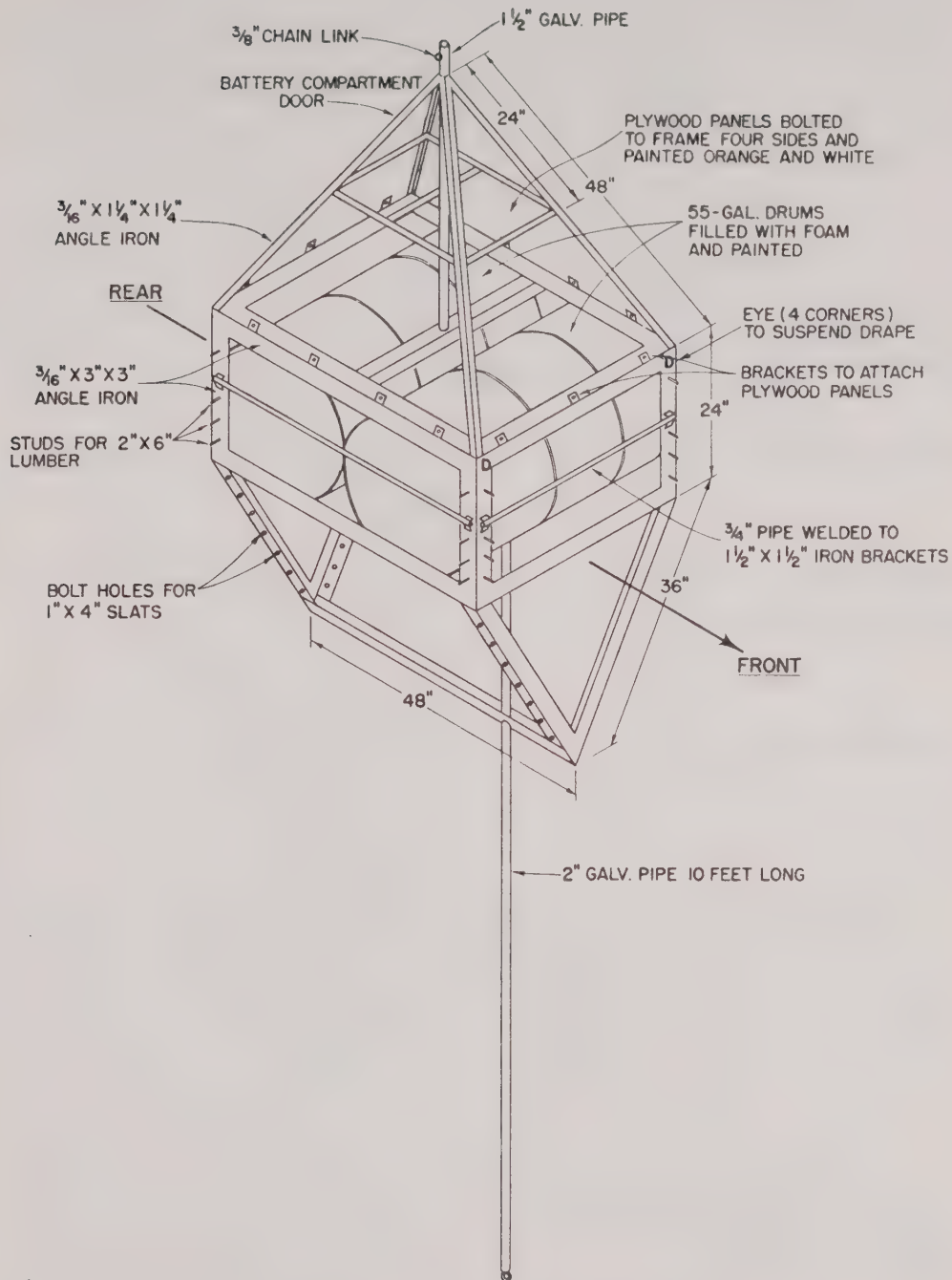


Figure 2.--Details of buoy.

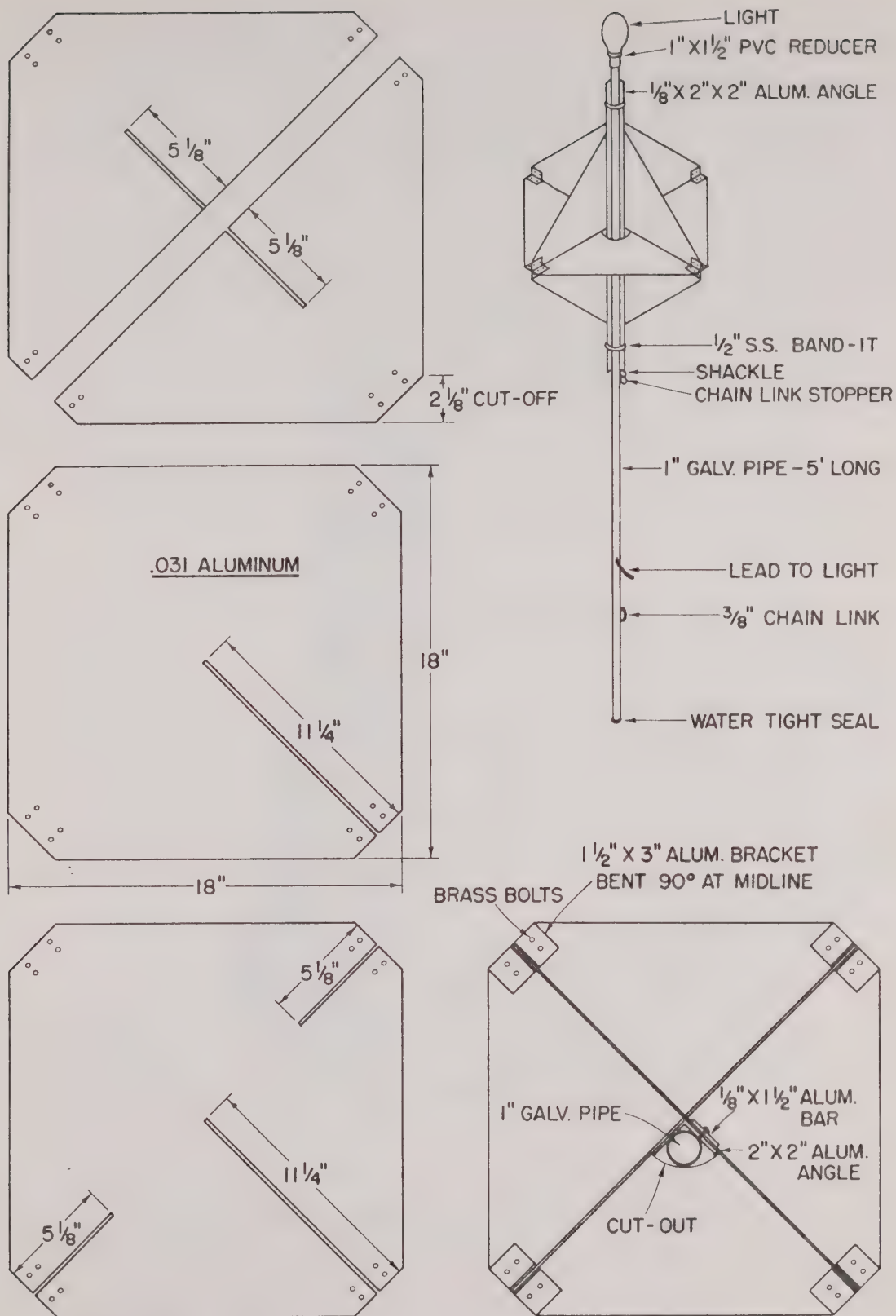


Figure 3.--Details of radar reflector.

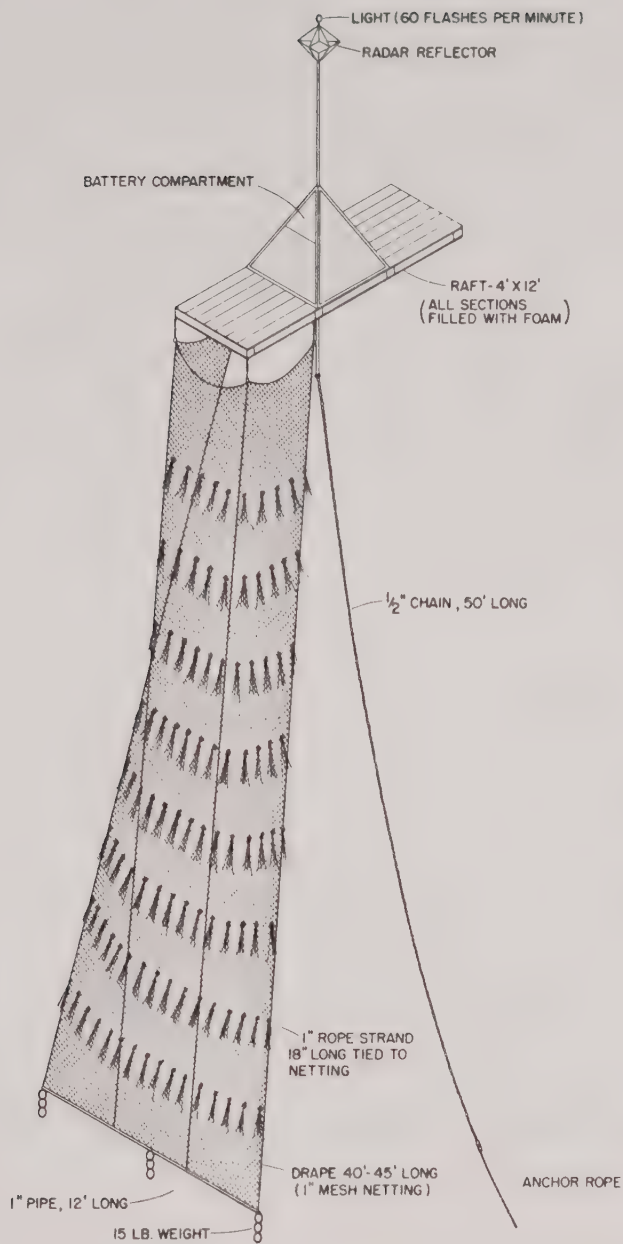


Figure 4.--Fish aggregating device, raft type.



Figure 5.--Fish aggregating devices off Oahu, Lanai, and Hawaii.

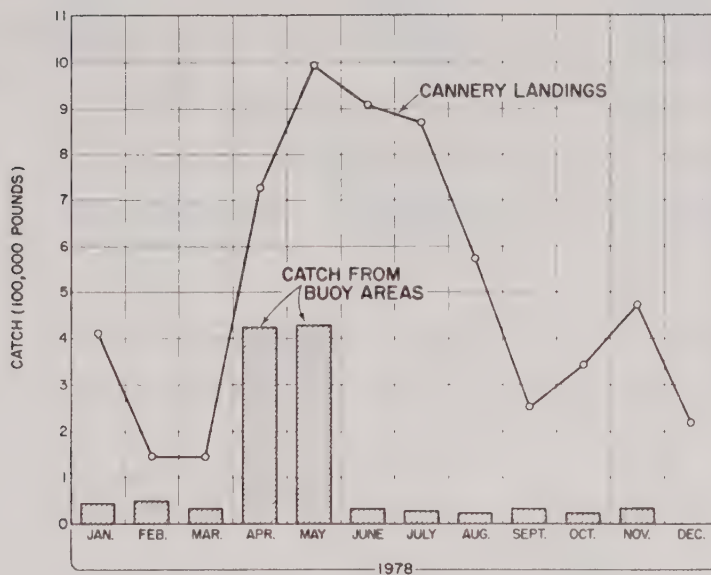


Figure 6.--Monthly catches of skipjack tuna around the buoys compared with monthly landings of skipjack tuna at Hawaiian Tuna Packers, December 1977-December 1978.

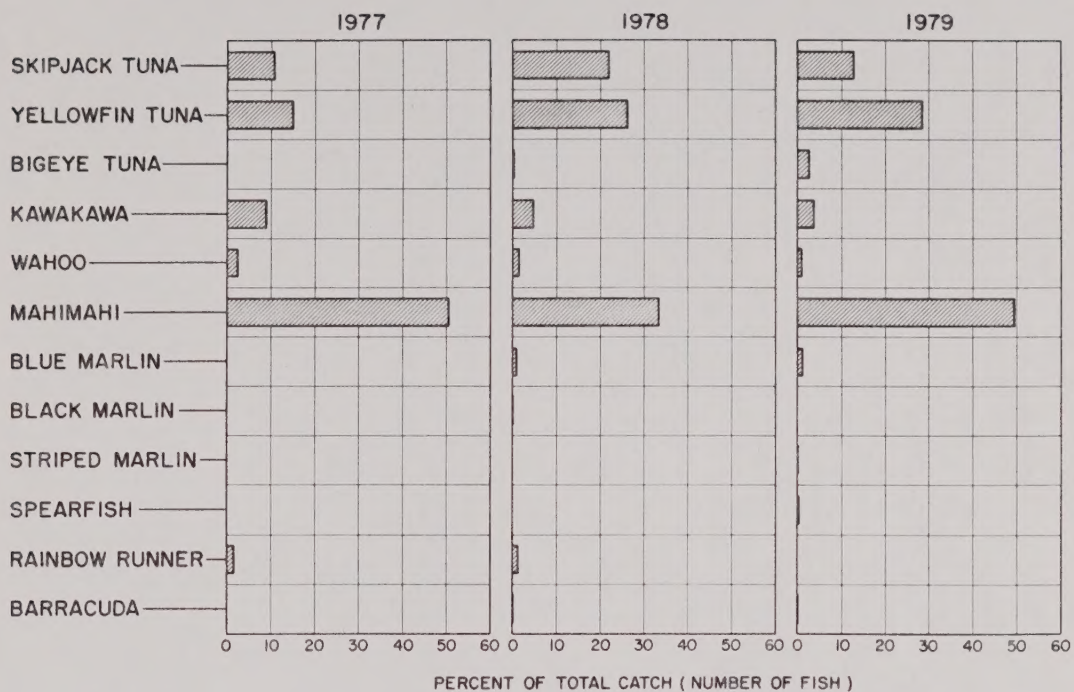


Figure 7.--Species of fish taken at buoys A, B/E, and C by trolling boats.

